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AN IMPROVED NUMERICAL PROCEDURE FOR THE PARAMETRIC OPTIMIZATION OF THREE DIMENSIONAL SCRAMJET NOZZLES

By

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SECTION I

INTRODUCTION

This report describes a parametric numerical procedure permitting the rapid determination of the performance of a class of scramjet nozzle configurations The geometric complexity of these configurations rules out attempts to employ conventional nozzle design procedures, Reference (1), wherein properties at the nozzle exit plane are specified and wave cancellation techniques are then employed to design the wall surfaces. It is not feasible to stipulate exit conditions á priori and wave cancellation techniques employing three dimensional characteristics are beyond the current state of the art.

The current approach is an extension of work discussed in Reference (2) and employs a characteristic grid network with Riemann invariants as variables. Lateral expansion effects are incorporated via one dimensional approximations as suggested in Reference (3).

The numerical program developed permits the parametric variation of cowl length, turning angles on the cowl and vehicle undersurface and lateral expansion and is subject to fixed constraints such as the vehicle length and nozzle exit height. The program requires uniform initial conditions at the burner exit station and yields the location of all predominant wave zones, accounting for lateral expansion effects. In addition, the program yields the detailed pressure distribution on the cowl, vehicle undersurface and fences, if any, and calculates the nozzle thrust, lift and pitching moments. Viscous effects are included in the latter via the Spalding-Chi method described in Reference (4). Local heat transfer coefficients are computed from a modified Reynolds' analogy. Local vehicle external flow interaction and/or plume boundary effects are computed insofar as they affect vehicle under surface pressure distributions.

Due to the differing techniques required for the calculation of ideal gas flows as compared to equilibrium flows, two separate numerical programs have been developed. The first program analyzes constant γ ideal gas flow fields and a listing of this program is provided in Appendix II. The second

program analyzes equilibrium hydrogen-air flow fields via equilibrium curve fits and its listing is provided in Appendix III. A complete program description is provided in Appendix I.

SECTION II

NUMERICAL PROCEDURES

Consider a typical nozzle configuration as depicted in Figure (1), where the lateral expansion distribution Z(x) may result from a combination of several nozzles merging into a single nozzle. It is assumed in this preliminary analysis that the jets after merging are bounded by sidewalls which extend downstream of the merged section. The initial flow (at the burner exit) is represented as an average uniform flow. The assessment of nonuniformities at the entrance station may be obtained applying the numerical procedure described in Reference (5).

A. Ideal Gas Grid Point Calculation - Consider the calculational procedure required to determine the location and properties of a point 3 (as shown in Figure 2) where properties at 1 and 2 are known and 1-3 and 2-3 are characteristic surfaces. Along these surfaces the Riemann invariants are defined as

$$C_{\pm} = \nu \mp \theta \tag{1}$$

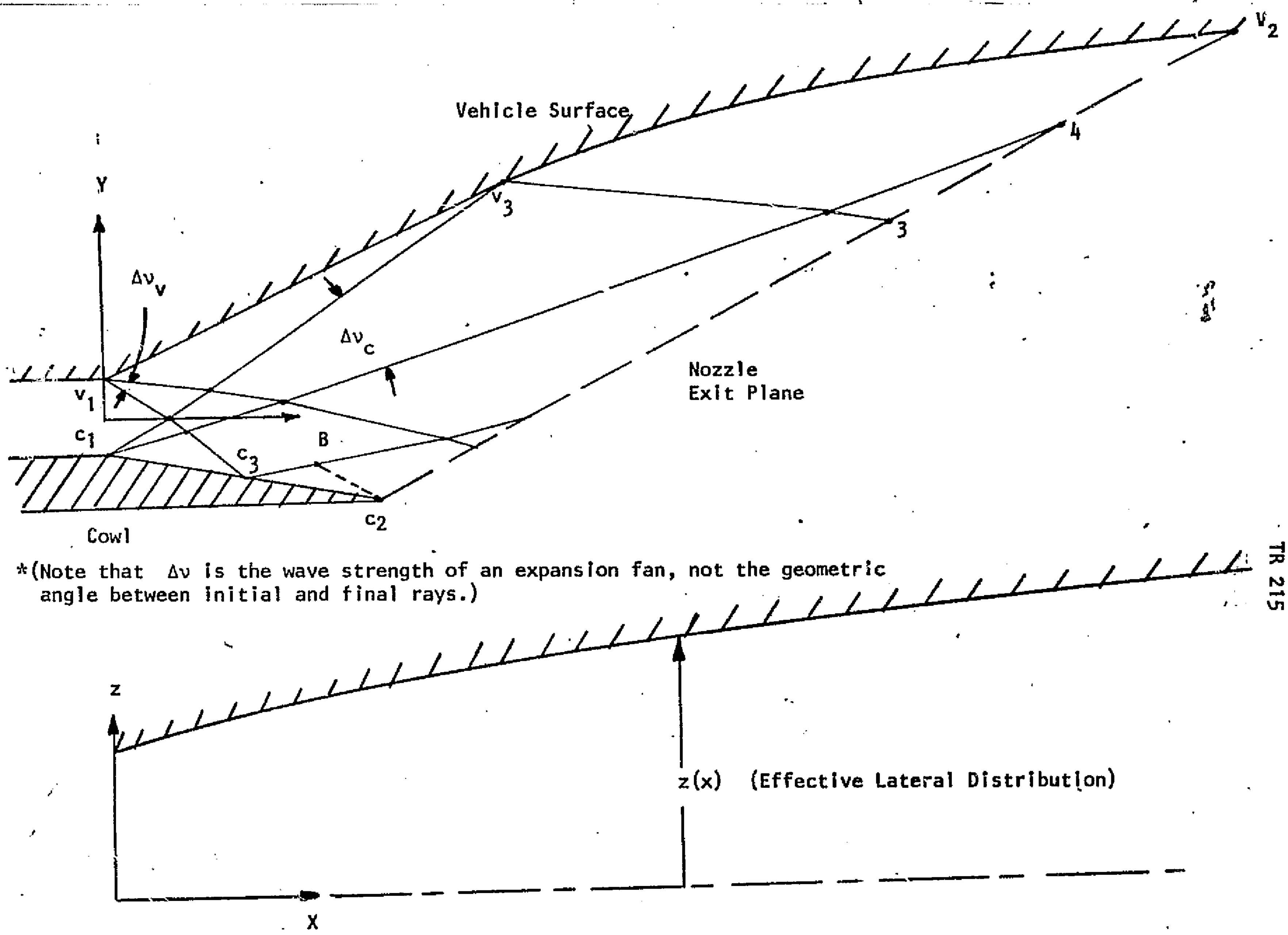
where ν is the Prandtl-Meyer function and θ the local flow deflections. Then at point 3

$$\nu_3 = \frac{1}{2}(\nu_1 + \nu_2) + \frac{1}{2}(\theta_1 - \theta_2) \tag{2a}$$

$$\theta_3 = \frac{1}{2}(\nu_1 - \nu_2) + \frac{1}{2}(\theta_1 + \theta_2) \tag{2b}$$

Employing the two dimensional value of expansion $\Delta\nu_3$ (from initial condition i) the Mach number M_3 is obtained via the Prandtl-Meyer relation (where i denotes uniform initial flow properties at the burner exit)

$$\Delta\nu_3 = \nu_3 - \nu_i = \sqrt{\frac{\gamma+1}{\gamma-1}}\left(\tan^{-1}\sqrt{\left(\frac{\gamma-1}{\gamma+1}\right)(M_3^2-1)} - \tan^{-1}\sqrt{\left(\frac{\gamma-1}{\gamma+1}\right)(M_i^2-1)}\right)$$
$$- \left(\tan^{-1}\sqrt{M_3^2-1} - \tan^{-1}\sqrt{M_i^2-1}\right) \tag{3}$$



*(Note that $\Delta\nu$ is the wave strength of an expansion fan, not the geometric angle between initial and final rays.)

FIGURE 1. TYPICAL NOZZLE CONFIGURATION

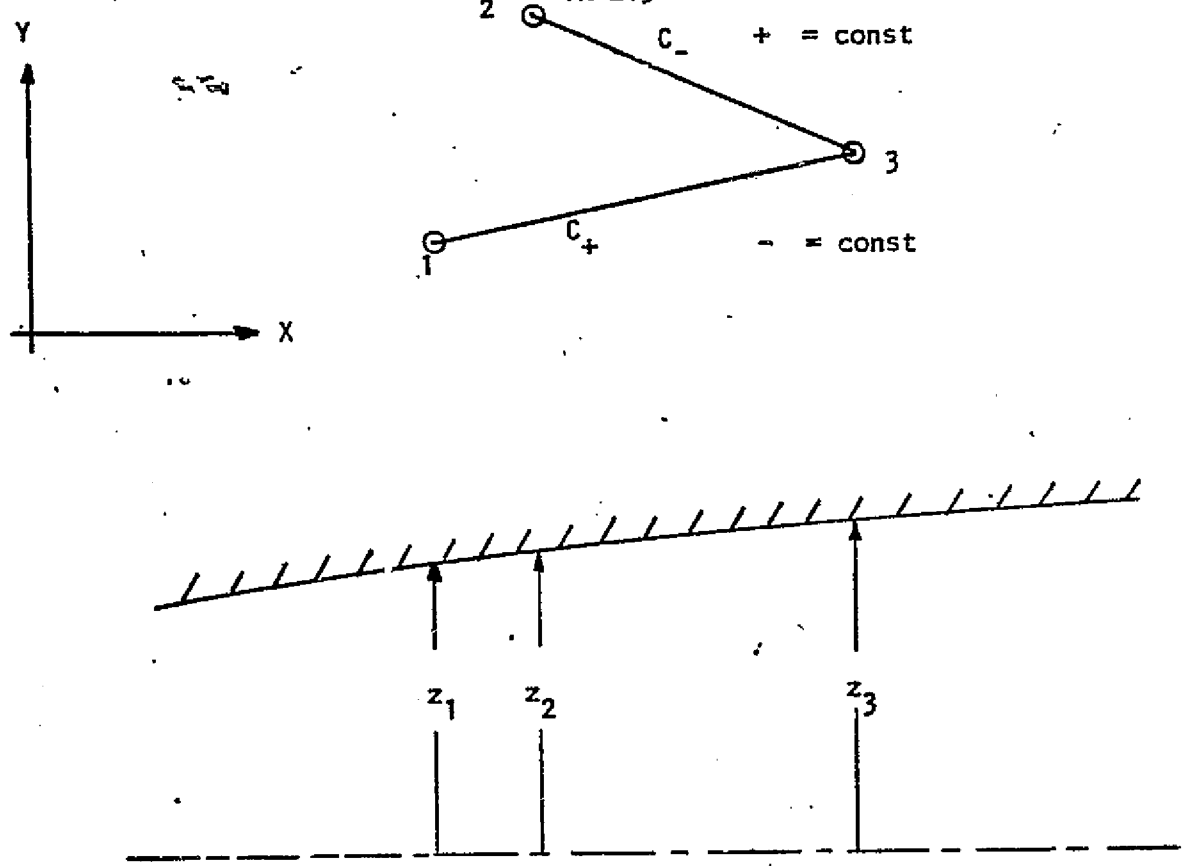


FIGURE 2. GRID POINT CALCULATION

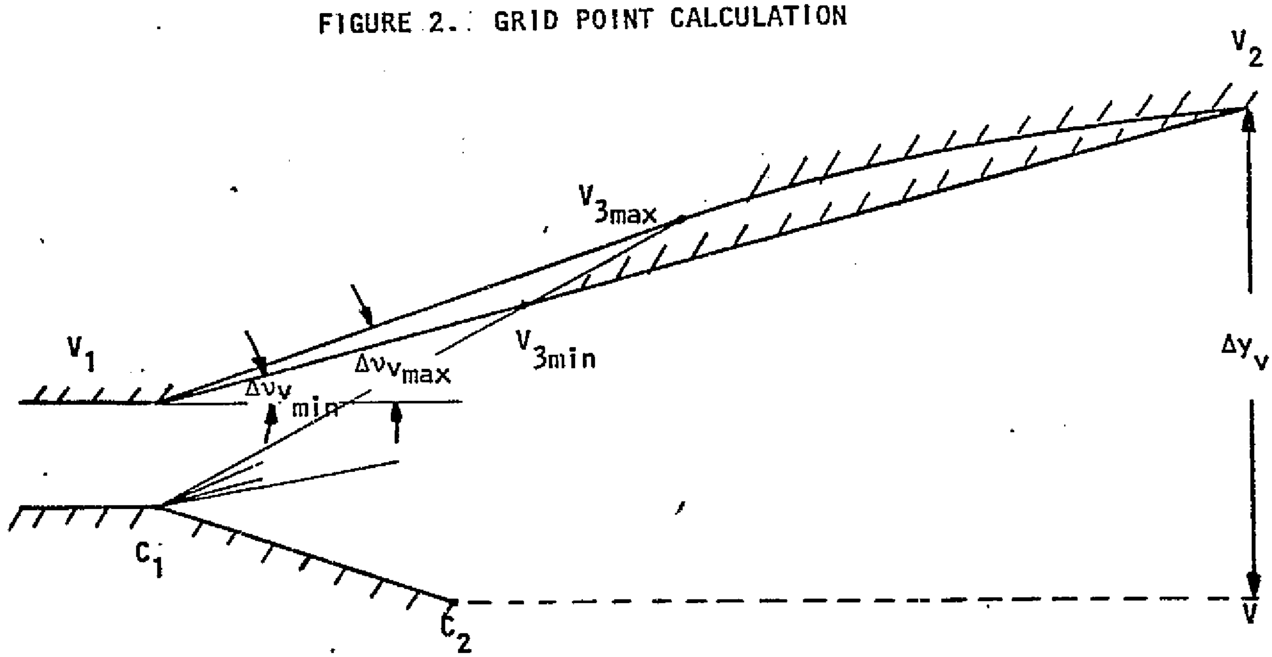


FIGURE 3. VARIATION OF VEHICLE EXPANSION WAVE STRENGTH

employing an iterative procedure to solve this transcendental equation for M_3. Then, with the Mach angle determined

$$\mu_3 = \sin^{-1} \left(\frac{1}{M_3}\right) \tag{4}$$

Equations (7a) and (7b) yield a tentative location for point 3, and the area ratio $(A/A^*)_3$ is calculated based on two dimensional considerations.

$$\left(\frac{A}{A_*}\right)_3 = \frac{\left(1 + \frac{\gamma-1}{2} M_3^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{M_3 \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \tag{5}$$

This ratio is corrected for lateral expansion by multiplying it by the ratio Z_3/Z_i where the lateral expansion variable is expressed by a suitable polynomial curve fit

$$Z(x) = Ax^2 + Bx + C \tag{6}$$

where $Z_3 = Z(x_3)$ and Z_i denotes the lateral extent of the nozzle at the initial station. The location $(x,y)_3$ is determined from

$$\frac{y_3 - y_{1,2}}{x_3 - x_{1,2}} = \frac{1}{2} \left[\tan(\theta_{1,2} \pm \mu_{1,2}) + \tan(\theta_3 \pm \mu_3)\right] \tag{7a,b}$$

then

$$\left(\frac{A}{A_*}\right)_3' = \left(\frac{A}{A_*}\right)_3 * Z_3/Z_i \tag{8}$$

The three dimensional corrected Mach number is obtained by replacing the two dimensional area ratio in Equation (5) by the three dimensional value given by Equation (8), and solving Equation (5) for $M_{3_{3D}}$ by an iterative process.

Equations (7a) and (7b) are resolved using the corrected Mach angle $\mu 3_{3D}$ and the entire procedure is repeated until two successive values of x_3 agree to within a prescribed tolerance.

A similar procedure is used to determine properties at grid points on boundaries with Equation (7a) or (7b) replaced with an equation describing the body geometry. Desired variables (P, T etc.) are then simply obtained by isentropic, constant γ expansions from initial conditions.

B. Equilibrium Flow Grid Point Calculation - The geometric location of point 3 is obtained employing Equations (7a) and (7b) and properties $(\nu,\theta)_3$ are obtained using Equations (2a,b) just as for the frozen calculation. The known two dimensional value of expansion $\Delta\nu_3 = \nu_3 - \nu_2$ is subdivided into a series of small $\Delta\nu_j$ increments. The initial value of isentropic exponent is obtained from

$$\Gamma = \Gamma\ (P,\ \phi,\ h) \tag{9}$$

where Equation (9) has been curve fit for equilibrium hydrogen-air as described in Reference (5).

The characteristic compatibility relation

$$\frac{d\ \ln P}{\Gamma} + \frac{d\ \nu}{\sin\mu\ \cos\mu} = 0 \tag{10}$$

applied across the interval $\Delta\nu_j$ yields the pressure, holding μ and Γ equal to their value at the start of the increment. The density is obtained from the isentropic pressure-density relation

$$P/\rho^{\Gamma} = \text{constant} \tag{11}$$

The velocity is obtained from the Bernoulli relation;

$$\frac{dP}{\rho} + \frac{1}{2} dV^2 = 0 \tag{12}$$

the enthalpy from the constancy of stagnation enthalpy;

$$h + \frac{1}{2} V^2 = H = \text{constant} \tag{13}$$

and the Mach number from;

$$M = V/a; \quad a = \left(\frac{\Gamma P}{\rho}\right)^{\frac{1}{2}} \tag{14}$$

where Γ has been reevaluated employing Equation (9). This procedure is repeated in small steps $\Delta\nu_j$ until the full wave $\Delta\nu_3$ has been integrated. Having the two dimensional value of M_3, point 3 can be tentatively located employing Equations (7a) and (7b). Then, the two dimensional area ratio can be computed from mass flow considerations

$$(A_3/A_i)_{2D} = \rho_i V_i / \rho_3 V_3 \tag{15}$$

Since the effective area based on three dimensional considerations is

$$(A_3/A_i)_{3D} = (A_3/A_i)_{2D} * Z_3/Z_i \tag{16}$$

the product $\rho_3 V_3$ must be divided by Z_3/Z_i to conserve mass flow

$$(\rho_3 V_3)_{3D} = (\rho_3 V_3)_{2D} * \frac{Z_i}{Z_3} \tag{17}$$

Then an iteration procedure is performed to determine the value of three dimensional expansion $(\Delta\nu_3)_{3D}$ The correct value being that which yields $(\rho_3 V_3)_{3D}$ after application of the integration procedure of Equations (9) thru (14), and an update of the location of point 3 using Equations (7a) and (7b)

SECTION III

DETERMINATION OF NOZZLE FLOW FIELDS

A nozzle calculation is performed subject to the following constraints:

1. The initial profile is uniform. For the frozen flow (constant γ) calculation this requires specification of the pressure p_i, flow deflection angle θ_i, Mach number M_i, and specific heat ratio γ. Fo the equilibrium calculation one must specify P_i, θ_i, M_i, the temperature T_i and the fuel-air equivalence ratio Φ_i.

2. The initial turning at the vehicle undersurface ($\Delta\nu_v$) and cowl ($\Delta\nu_c$) occur via sharp corners as depicted in Figure (1).

3. The wall segments downstream of these sharp corners remain straight until the expansion waves emanating from the cowl and vehicle undersurface reach the walls (points V_3 and C_3 of Figure 1).

4. The nozzle exit height is specified ($y_{v_2}-y_{c_2}$).

5. The recompression on the vehicle undersurface (between V_3 and V_2) is parabolic while the cowl between is straight, (i.e., constant slope from C_1 to C_3).

6. The lateral expansion $Z(x)$ is specified via a geometric curve fit.

7. The cowl length and vehicle length are specified.

8. Local cowl external flow properties are specified.

The numerical logic employed in the parametric design procedure is to treat the cowl length ($x_{c_2}-x_{c_1}$) and the vehicle undersurface expansion $\Delta\nu_v$ as

parametric variables for fixed values of cowl turning $\Delta\nu_c$, nozzle exit height, lateral expansion and vehicle length. Initially, a short cowl length should be chosen such that the expansion waves from the vehicle expansion fan miss the cowl. For this cowl length, the value of the vehicle undersurface expansion wave is varied in small increments, the minimum amount of turning being that which introduces no recompression in the region V_3 to V_2 (i.e., the undersurface has no curvature) to a value for which the recompression produces zero deflection at the end of the vehicle. This is illustrated in Figure (3). Then the cowl length is increased in specified increments and the entire procedure is repeated.

For a given nozzle configuration, the calculational procedure is as follows: Point V_2 is located and vehicle expansion $(\Delta\nu_V)_{min}$ is determined and semented into small increments $(\Delta\nu_i)_V$. The cowl expansion array is swept out by segmenting $\Delta\nu_c$ into small segments $(\Delta\nu_i)_c$ and the interaction of each ray with the vehicle expansion is determined upto the vehicle surface (or exit plane) as discussed in Section II.

After completing the cowl expansion, it must be determined whether the first ray from the vehicle expansion intersects the cowl surface. If not, properties at C_2 are determined by inserting a data point B (Figure 4) on the final cowl ray such that the characteristic BC_2 intersects point C_2. The reflected ray at C_2 is computed upto the vehicle surface or until the exit plane is crossed. If the first vehicle ray does intersect the cowl before C_2 the intersection is determined and the reflected ray computed up to the vehicle undersurface or upto the exit plane. The calculation proceeds to the next vehicle expansion ray and the above repeated until Point C_2 is reached. Note if the vehicle surface is chosen sufficiently long all cowl rays may be "captured" on the vehicle. In this case the local external flow and/or plume shape may affect the vehicle undersurface pressure distribution. The program automatically determines if such a calculation is to be performed. Figures (4) through (9) illustrate typical exit conditions.

Upon completion of the minimum vehicle turning configuration, the vehicle expansion is incremented by a specified amount and the above process repeated

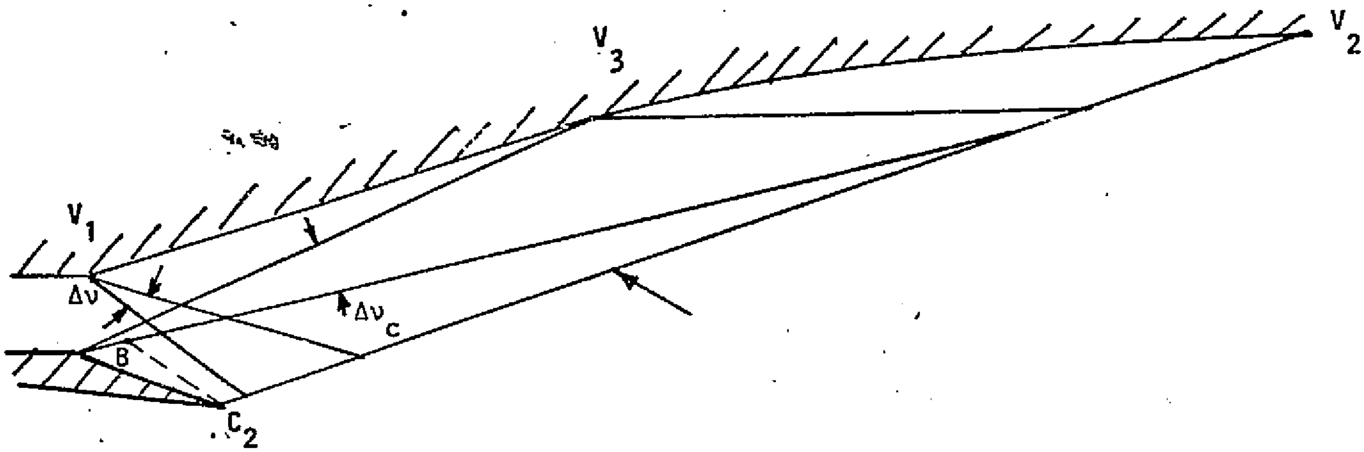


FIGURE 4. PARTIAL REFLECTION OF COWL EXPANSION/ NO REFLECTION OF VEHICLE EXPANSION

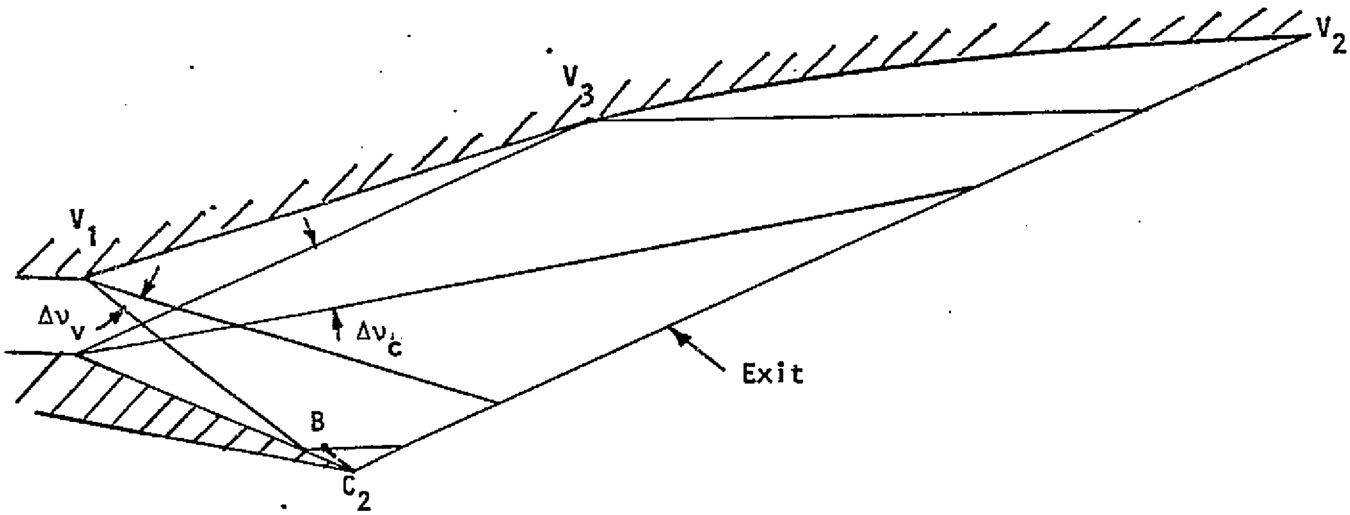


FIGURE 5. PARTIAL REFLECTION OF COWL AND VEHICLE EXPANSIONS

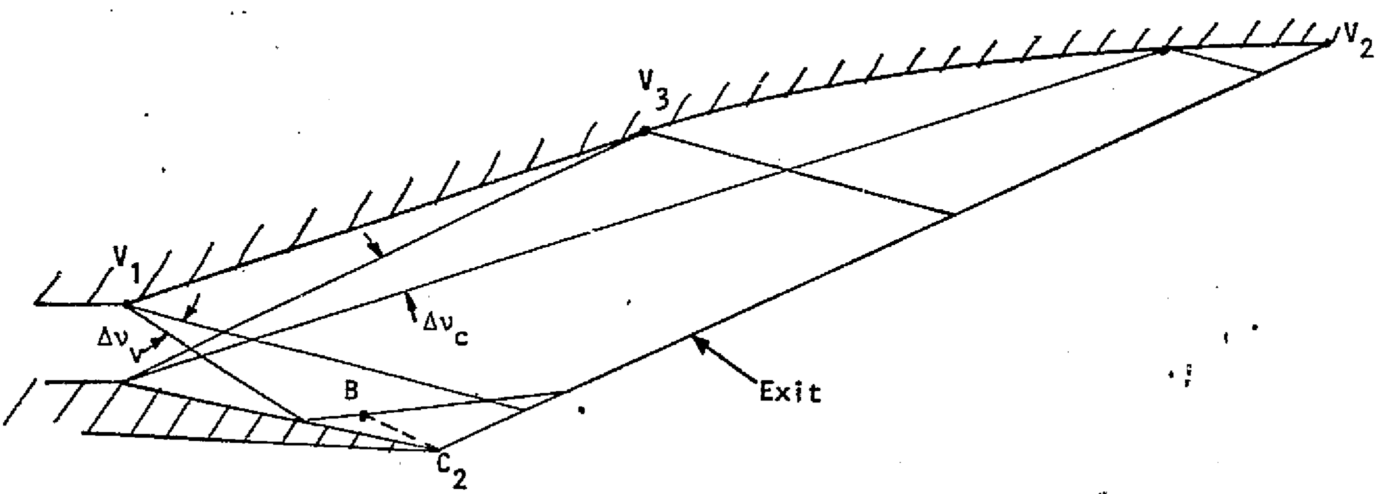


FIGURE 6. COMPLETE REFLECTION OF COWL EXPANSION/ PARTIAL REFLECTION OF VEHICLE EXPANSION

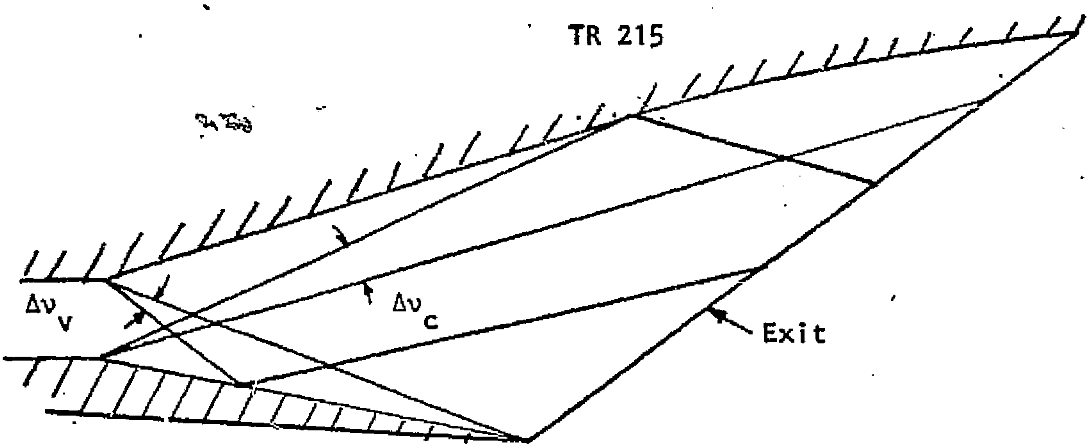


FIGURE 7. PARTIAL REFLECTION VEHICLE EXPANSION/
COMPLETE REFLECTION OF COWL EXPANSION

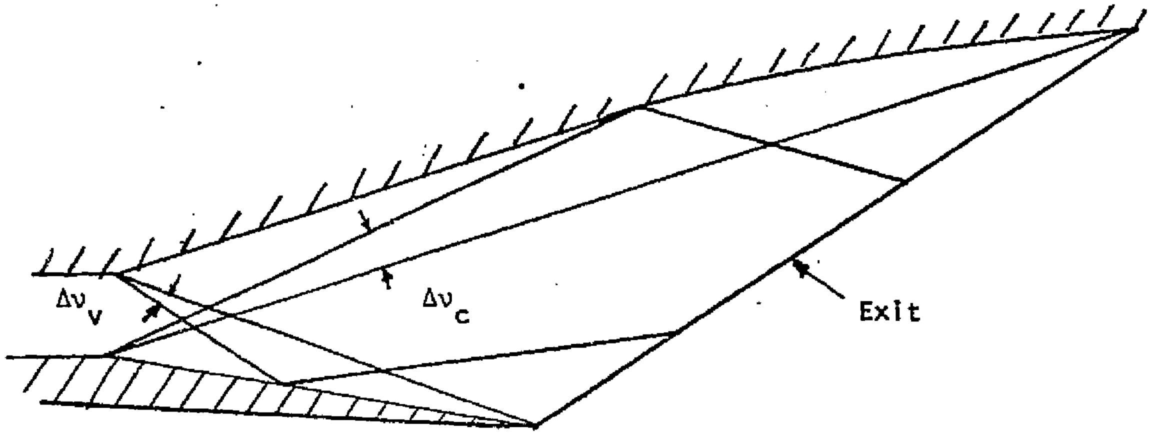


FIGURE 8. COMPLETE REFLECTION OF COWL AND VEHICLE EXPANSIONS

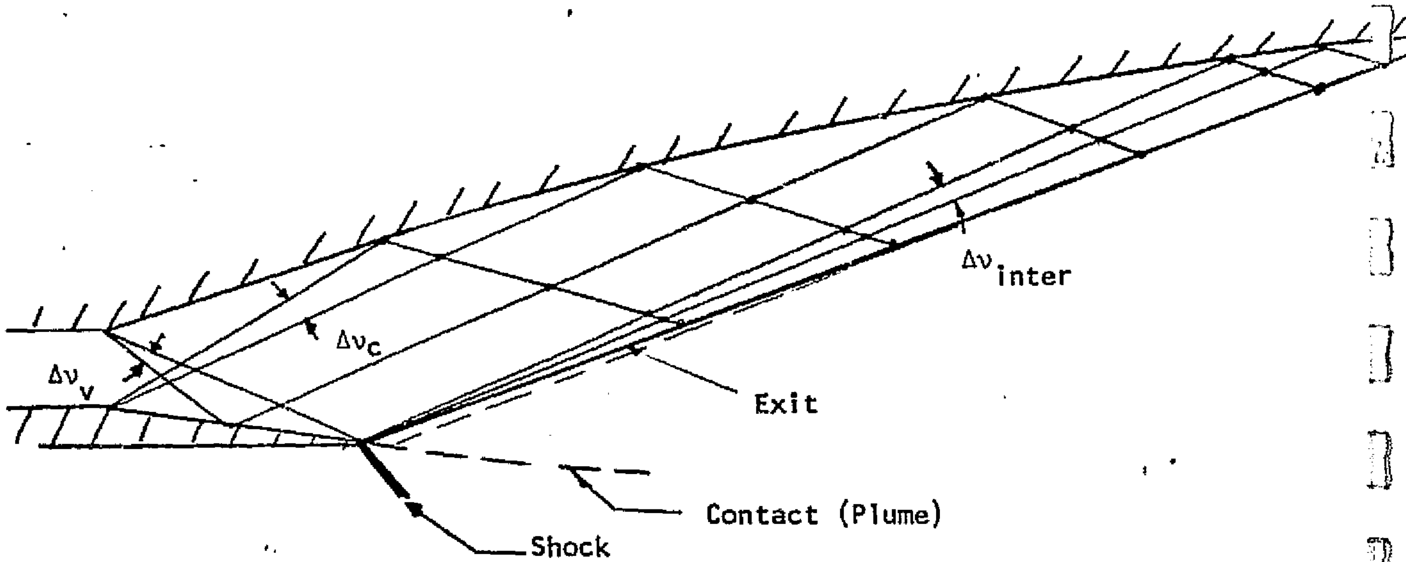


FIGURE 9. INTERACTION OF EXTERNAL FLOW WITH VEHICLE UNDERSURFACE

until zero flow deflection results at point V_2. The cowl length is now incremented by a specified amount and the complete process repeated. In this manner a parametric map of lift, thrust and pitching moment is generated as depicted in Figures (10) and (11). The dotted lines are the present analysis for a oowl length of 5 and the solid lines were taken from the previous work described in Reference (2).

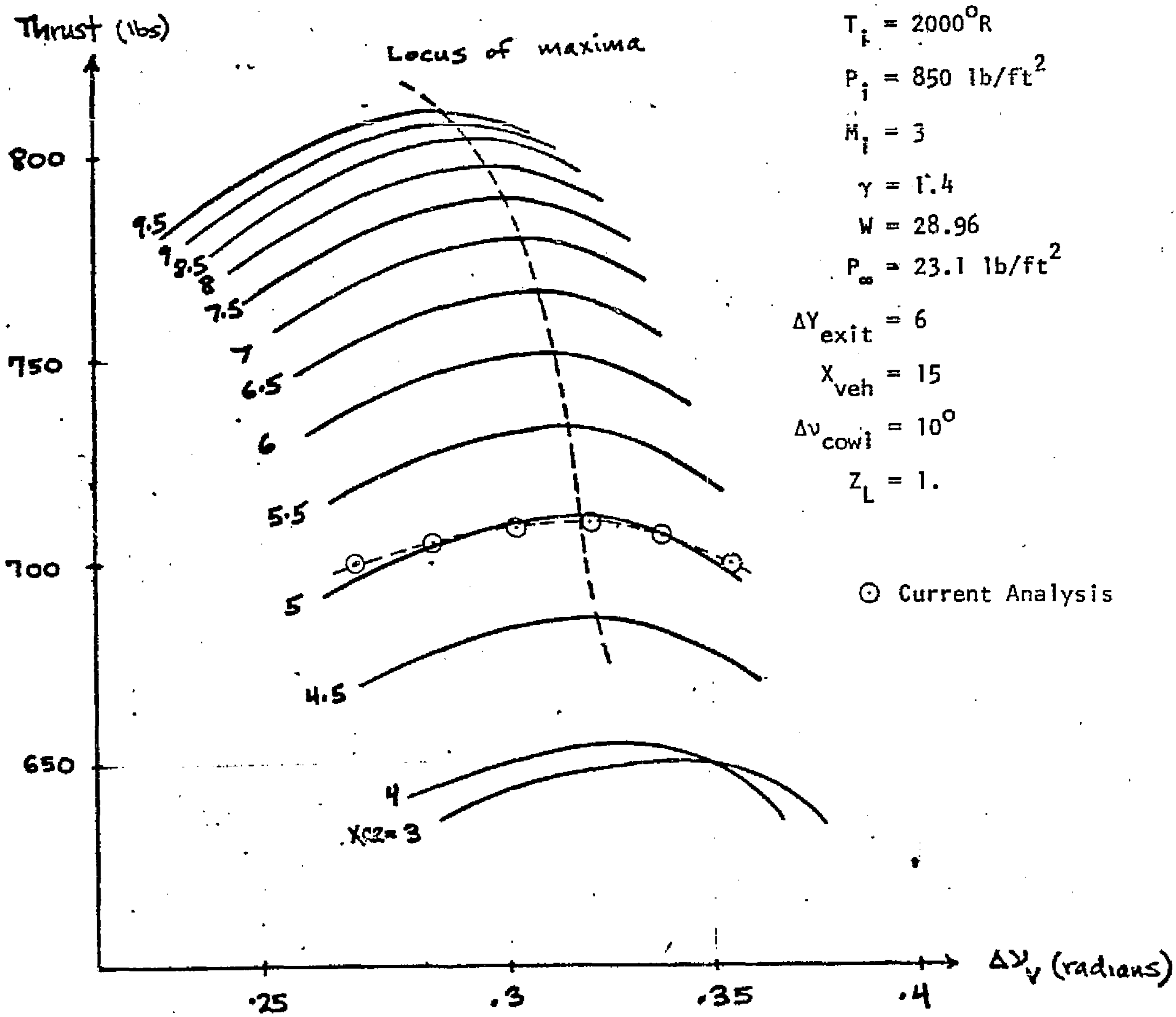


FIGURE 10. THRUST VARIATION WITH COWL LENGTH AND VEHICLE EXPANSION ANGLE

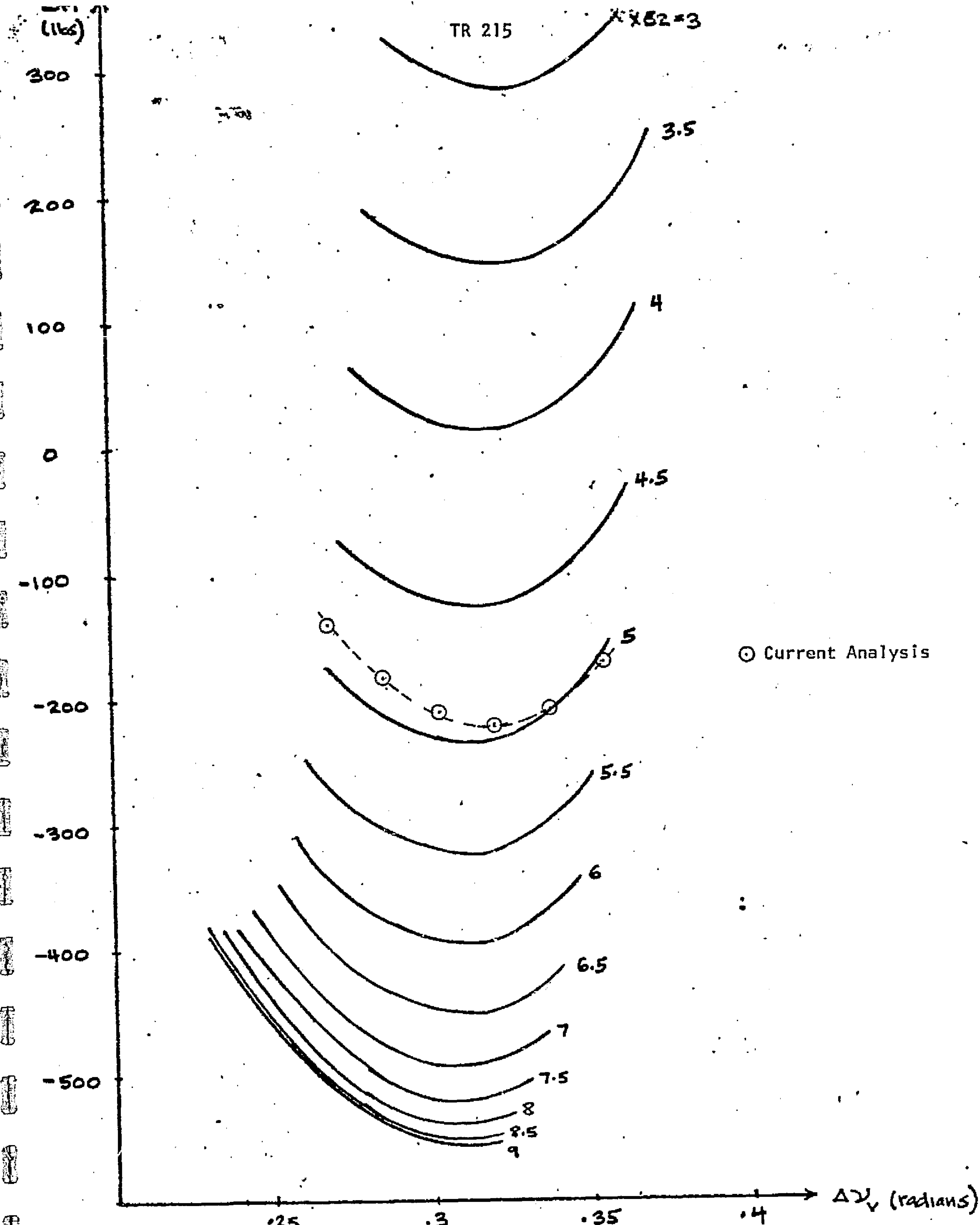


FIGURE 11. LIFT VARIATION WITH COWL LENGTH AND VEHICLE EXPANSION

SECTION IV

THRUST, LIFT AND PITCHING MOMENT

The following definitions are used in this report for thrust, lift, pitching moment

$$T = \int_A (p-p_\infty) \ \hat{i}_x \cdot d\vec{A}_n + T_{vis} \tag{18}$$

$$L = \int_A (p-p_\infty) \ \hat{i}_y \cdot d\vec{A}_n + L_{vis} \tag{19}$$

$$M_y = + \int x \cdot dL + \int y \cdot dT \tag{20}$$

Figure (12) gives the orientation of the vectors with respect to the vehicle. Internally the integrals range over all the vehicle surface areas. Externally they range over the complete vehicle undersurface as defined by the bounding stream surface and/or flow fence.

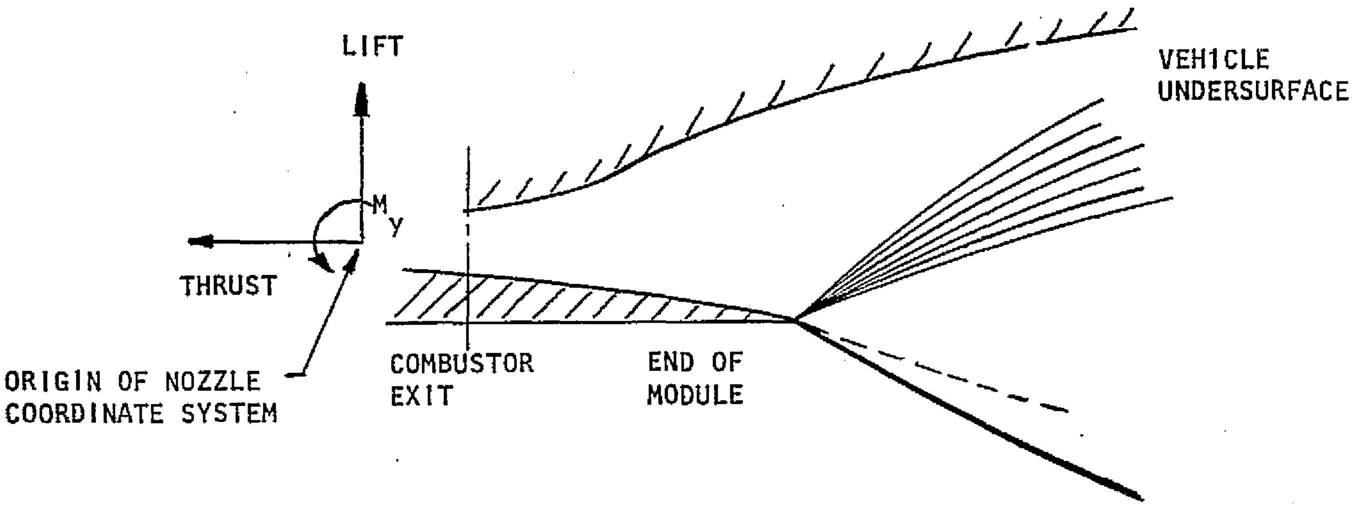


FIGURE 12. THRUST, LIFT, MOMENT

As defined above the nozzle thrust, lift and pitching may include viscous forces. These effects will be discussed below. However, we define T_{vis}, L_{vis} as

$$T_{vis} = - \int_A \left(\frac{\rho q^2}{2}\right)_{local} C_f \ \hat{i}_x \cdot d\vec{A}_s \qquad (21)$$

$$L_{vis} = - \int_A \left(\frac{\rho q^2}{2}\right)_{local} C_f \ \hat{i}_y \cdot d\vec{A}_s \qquad (22)$$

Surface Area Computation - Internally the nozzle surfaces are defined as the cowl internal surface, vehicle undersurface, and the nozzle sidewall. Externally the surfaces are defined as the nozzle undersurface and/or flow fences. The lateral extent of the cowl surface and nozzle undersurface is defined by the degree of lateral expansion desired.

It is assumed that the nozzle area can be approximated by a series of elemental quadrilaterals, as shown in Figure (13). From Reference (7) the unit normal for an elemental area may be obtained by defining two surface tangent vectors from the diagonals of the quadilateral.

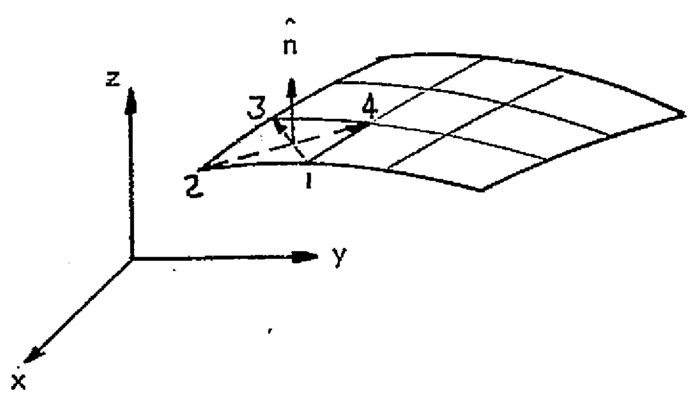


FIGURE 13. ELEMENTAL SURFACE AREA

That is

$$\vec{T}_1 = T_{1x}\,\hat{i}_x + T_{1y}\,\hat{i}_y + T_{1z}\,\hat{i}_z \tag{23a}$$

$$\vec{T}_2 = T_{2y}\,\hat{i}_x + T_{2y}\,\hat{i}_y + T_{2z}\,\hat{i}_z \tag{23b}$$

where

$$T_{1x} = x_3 - y_2, \quad T_{1y} = y_3 - y_1, \; T_{1z} = z_3 - z_1$$

$$T_{2x} = x_4 - y_2, \quad T_{2y} = y_4 - y_2, \; T_{2z} = z_4 - z_2$$

and the normal $\vec{N}$ is defined as

$$\vec{N} = T_2 \times T_1$$

and the unit normal as

$$\hat{n} = \frac{\vec{N}}{|\vec{N}|} \tag{24}$$

A tangent plane is constructed using the normal vector and the two tangent vectors $\overline{T}_2$, $\overline{T}_1$. The corners of the surface element are projected onto this plane and the area and centroid of the quadilateral are calculated as described in Reference (7).

Typical nozzle elemental areas are shown in Figures (14) and (15)

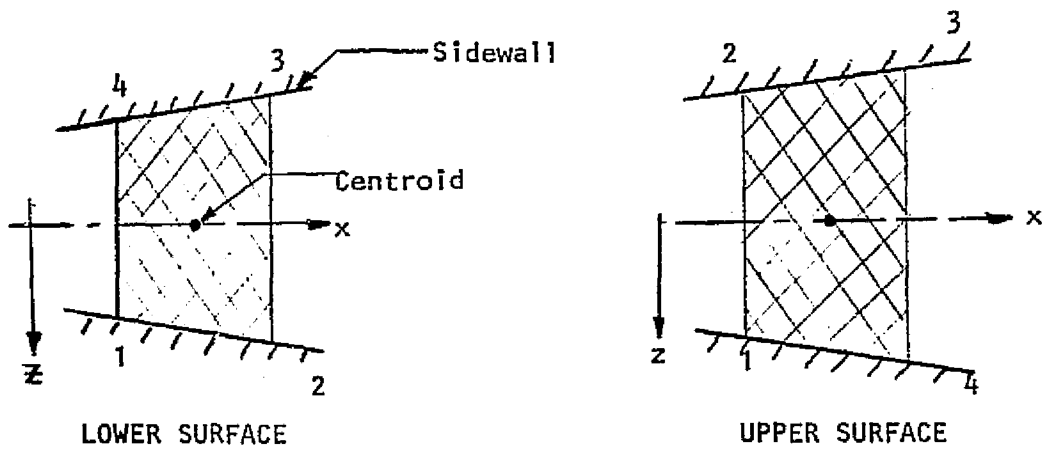


FIGURE 14. UPPER OR LOWER SURFACE AREA ELEMENTS

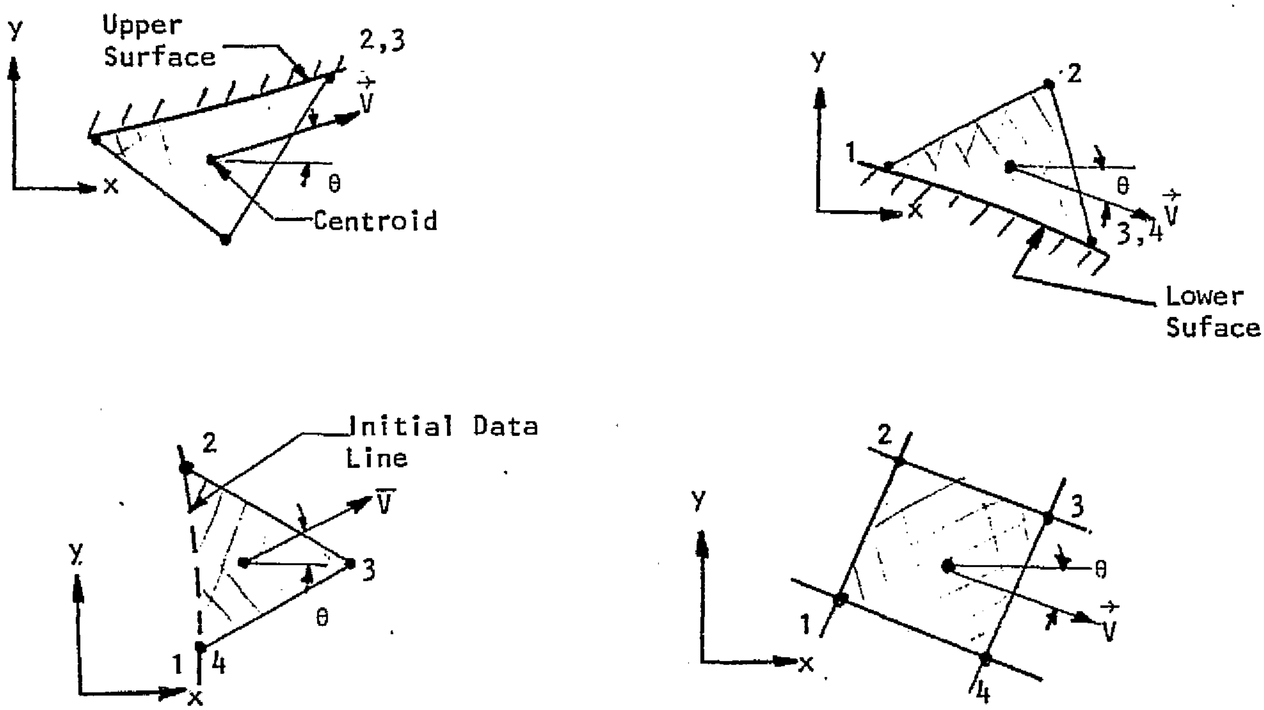


FIGURE 15. SIDEWALL AREA ELEMENTS

SECTION V

VISCOUS EFFECTS

Local skin friction and heat transfer coefficients are computed via curve fit data supplied from Reference (7). These fits are based on the Spalding and Chi method of Reference (4). That is a suitably transformed skin-friction coefficient is given by incompressible formulas based on a suitably transformed Reynolds number, i.e.:

$$C_{f_\delta} = C_{f_i}/F_c \tag{25}$$

$$C_{f_i} = f(Rx_i), \quad Rx_i = F_{Rx} \cdot Rx \tag{26}$$

where

C_f = local skin friction coefficient

Rx = Reynolds number

$(\ )_i$ = indicates incompressible

$(\ )_\delta$ = indicates compressible

Now for $Rx_i > 2540$ the local skin friction is given from Reference (8) as

$$C_{f_i} = .088\ (\log Rx_i - 2.3686)/(\log Rx_i - 1.5)^3 \tag{27}$$

and from Reference (7)

$$F_c = A/\left(\text{ARSIN}\ \left(\frac{A-B}{C}\right) + \text{ARSIN}\ \left(\frac{A+B}{C}\right) \right)^2 \tag{28}$$

$$A = \frac{H_{AW}}{H_\delta} - 1 \tag{29a}$$

$$B = \frac{H_W}{H_\delta} - 1 \tag{29b}$$

$$C = ((A+B)^2 + 4A)^{1/2} \tag{29c}$$

$$F_{Rx} = \left(\frac{H_{AW}}{H_\delta}\right)^q / \left(F_c \left(\frac{H_W}{H_\delta}\right)\right)^{p+q} \quad , q = 0.772,\ p = 0.702 \tag{30}$$

The local properties external to the boundary layer are the local data computed by frozen (NOZD) or equilibrium (NOZDE) programs and are assumed to act through the centroid of the elemental area computed above. The computation requires that a boundary layer origin be specified since the nozzle is assumed to be an extension of the combustor. In addition, a recovery factor for an adiabatic wall calculation is required. However, as a user option wall temperature distributions may be specified.

Local heat transfer coefficients are computed from a modified Reynolds analogy for turbulent flow

$$St = Sh \cdot C_f/2 \tag{31}$$

The program requires "Sh" as an input item.

SECTION VI

CONCLUSIONS

The numerical program developed should be a useful tool in rapidly assessing the affects of varying dominant parameters on scramjet exhaust nozzles. The program has the capability of analyzing a general class of scramjet nozzle configurations. Sophisticated force and moment calculations allow for the inclusion of local viscous affects and accurate computation of lateral forces. In addition, the effects of external flow conditions on nozzle performance may be rapidly assessed as part of the overall procedure. These features make the current program a valuable tool in designing scramjet nozzle configurations.

REFERENCES

1. Dash, S., "The Determination of Nozzle Contours for Rotational, Non-Homentropic Gas Mixtures," ATL TR 148, March 1970.

2. Dash, S., Del Guidice, P., and Kalben, P., "A Numerical Procedure for the Parametric Optimization of Three Dimensional Scramjet Nozzles," ATL TR 188, NASA CR 132440, October 1973.

3. Ferri, A., Dash, S. and Del Guidice, P., "Methodology for Three Dimensional Nozzle Design," ATL TR 195, March 1974

4. Spalding, D.B. and Chi, S.W., "Drag of a Compressible Turbulent Boundary Layer on a Smooth Flat Plate With and Without Heat Transfer," J. Fluid Mechanics, Vol. 18, Pt.1, January 1964.

5. Del Guidice, P., Dash, S. and Kalben, P., "A Source Flow Characteristic Technique for the Analysis of Scramjet Exhaust Flow Fields," ATL TR 186, March 1974.

6. Dash, S. and Del Guidice, P., "Analysis and Design of Three Dimensional Supersonic Nozzles," ATL TR 166, October 1972.

7. Gentry, A.E. and Smyth, D.N., "Hypersonic Arbitrary-Body Aerodynamic Computer Program, Mark II Version," Vol. II, Douglas Report DAC 61552, April 1968.

8. Sivells, J.C. and Payne, R.G., "A Method of Calculating Turbulent Boundary Layer Growth at Hypersonic Mach Numbers," AEDC TR 59-3, March 1959.

APPENDIX I

PROGRAM DESCRIPTION

NOZD - Frozen Nozzle Design

NOZDE - Equilibrium Nozzle Design

A. INPUT

Card 1 (Format 8E10.0)

Column	1-10	PI	(initial pressure, lb/ft^2)
	11-20	TI	(initial pressure, ^oR)
	21-30	wI	(initial molecular wt - frozen)
			(initial fuel/air equivalence ratio equilibrium)
	31-40	THI	(initial flow deflection angle, degrees)
	41-50	EMI	(initial Mach number)

*Frozen Deck

	51-60	GAMI	(initial ratio of specific heats)
	61-70	PINF	(free stream pressure, lb/ft^2)

*Equilibrium Deck

	51-60	PINF	(free stream pressure, lb/ft^2)

Card 2 (Format 8E10.0)

Column	1-10	PF	(external pressure, lb/ft^2)
	11-20	TF	(external temperature ^oR)
	21-30	wf	(external molecular weight)
	31-40	THF	(external flow deflection angle, degrees)
	41-50	EMF	(external Mach number)
	51-60	GF	(external ratio of specific heats)

Card 3 (Format 8E10.0)

Column	1-10	XV1	(axial location of throat on vehicle undersurface ft)
	11-20	YV1	(throat height on vehicle undersurface, ft)
	21-30	XV2	(axial location of vehicle end, ft)

Column	31-40	XCI	(axial location of throat on cowl surface, ft)
	41-50	YCI	(throat height on cowl surface, ft)
	51-60	XC2	(length to end of cowl, ft)
	61-70	DYV	(vehicle exit height, $Y_{v2} - Y_{c2}$, ft)
	71-80	DNUC	($\Delta\nu_c$ - cowl turning angle, degrees)

<u>Card 4</u> (Format 8E10.0)

Column	1-10	XFI	(axial location of vehicle fence on vehicle undersurface, ft)

<u>Card 5</u> (Format 8E10.0)

Column	1-10	XTHX	(total initial thrust, lbs)
	11-20	XLFT	(total initial lift, lbs)
	21-30	XMOM	(total initial pitching moment, lb-ft)
	31-40	XVTHX	(initial viscous thrust, lbs)
	41-50	XVLFT	(initial viscous lift, lbs)
	51-60	XVMOM	(initial viscous pitching moment, lb-ft)
	61-70	XSHFT	(x-moment axis, ft)
	71-80	YSHFT	(y-moment axis, ft)

<u>Card 6</u>		<u>Format</u>		
Column	1-5	I5	ICF	- number of different cowl lengths to be executed
	6-15	E10.0	DXC	- increment to be added to original cowl length x_{c_2}
	16-20	I5	JFT	- number of vehicle turning angles to be run for each cowl length
	21-30	E10.0	DTH	- increment for vehicle turning angle in degrees
	31-35	I5	IVIS	- option for viscous calculation - 0 if no calculation, 1 for calculation
	36-40	I5	IT	- option for wall temperature calculation; 0-calculate T_{wall}, 1-adiabatic wall

(If IVIS is equal to 1 read this card)

Card 6a (Format 8E10.0)

Column	1-10	XSTR	(virtual origin of boundary layer, ft)
	11-20	Rec	(recovery factor)
	31-40	SH	(constant for Stanton number calculation $St = SH \cdot CF/2.$)
	41-50	RT	(throat height, ft)

(If IT is equal to 0 read this card)

Card 6b (Format 8E10.0)

Column	1-10	AH(1)	coefficients in equation
	11-20	BH(1)	$T_{wall} = AH \cdot X^2 + BH \cdot X + CH$
	21-30	CH(1)	

Card 7 (Format 8E10.0)

Column	1-10	AZ	coefficients in equation
	11-20	BZ	$Z = AZ \cdot X^2 + BZ \cdot X + CZ$
	21-30	CZ	

B. OUTPUT

Output variables are printed for each uprunning characteristics (C_+) from cowl to vehicle surface or exit plane. In addition, values of thrust, lift and pitching moment are printed as well as the viscous contributions to these values. The value of ideal thrust printed is based on a one dimensional area considerations, assuming $A_{exit} = (YV2\text{-}YC2)\ (ZC_2+ZV_2)/2.$

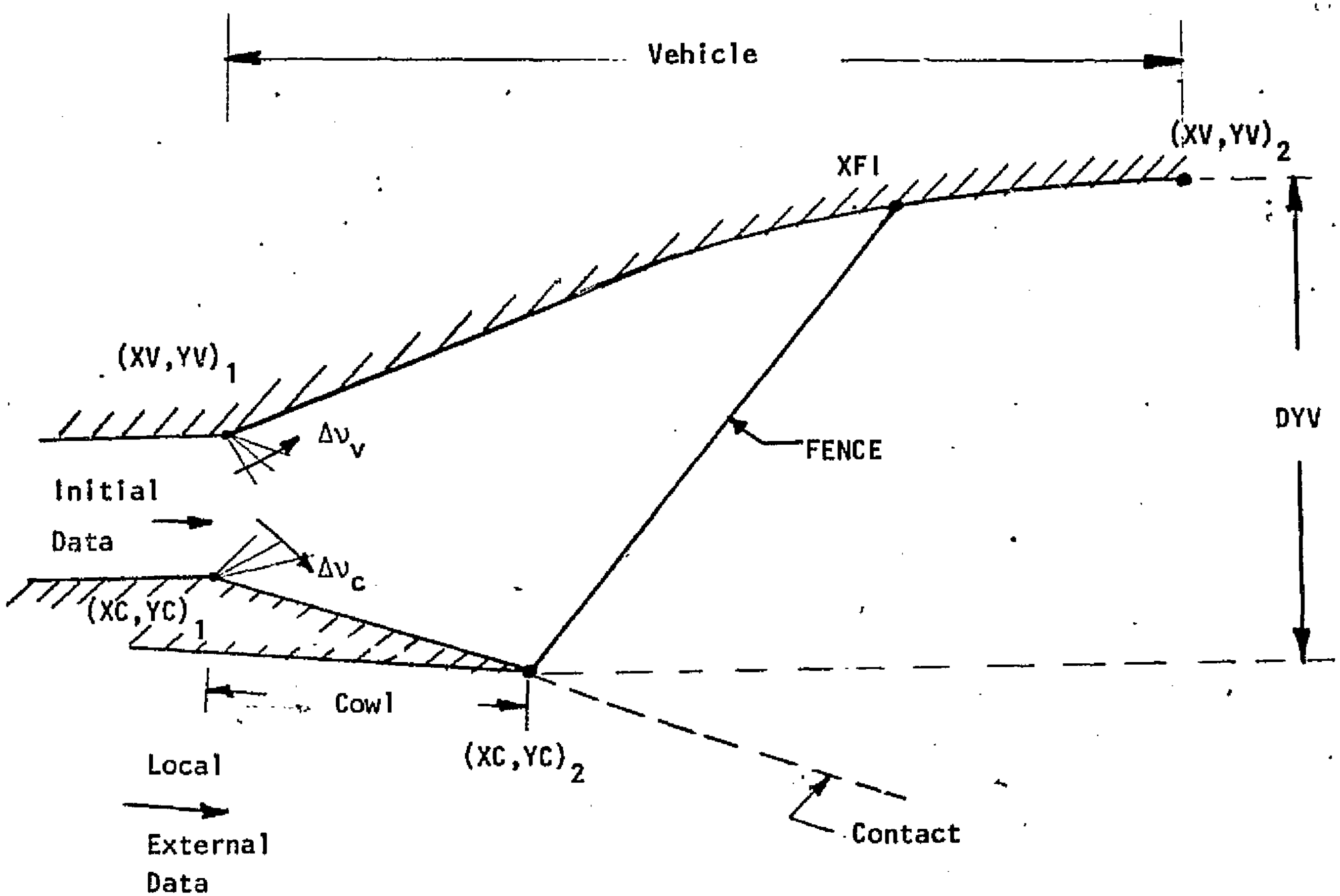


FIGURE 16. GEOMETRIC INPUTS

C. SUBROUTINES

1. CWALL - boundary calculation for cowl surface
2. ENDD - boundary point for vehicle end (XV2)
3. INT - interpolation subroutine
4. THM - computes ideal thrust
5. EM3D - computes Mach number correction for lateral expansion ideal gas only
6. SWITCH- resets initial calculational line
7. V_{WALL} - boundary calculation for vehicle surface
8. GEM - locations intersection of straight lines
9. FIX - computes general interior point properties as described in Section III
10. PM - calculates Prandtl-Meyer expansion for given $\Delta\nu$
11. GNURE - computes skin friction and heat transfer coefficients
12. VIS - computes viscosity
13. SNARF - computes elemental area and centroid
14. LTHM - computes lift, thrust and pitching moment for cowl, vehicle and fence surfaces
15. ERROR - Newton-Raphson method for finding roots
16. CNT - Commutes local plume shape
17. COWL - computes underexpansion interaction
18. PMI - ideal gas Prandtl-Meyer expansion - equilibrium program only

D. FUNCTIONS

1. GETZ - computes z location via curve $z = A \cdot X^2 + B \cdot X + C$

(The following are incorporated only into the equilibrium deck)

2. FH - computes static enthalpy of equilibrium mixture,
$H = FH(P, \phi, T)$

3. FT - computes static temperature from inversion of function, FH
$T = FT(P, \phi, H)$

4. FGAM- computes equilibrium isentropic component, $\Gamma = FGAM(T, P, \phi)$

5. RHEQ- computes equilibrium mixture density,
$\rho = RHEQ(H, P, \phi, T)$

APPENDIX II

LISTING OF FROZEN FLOW PROGRAM

```
      PROGRAM NOZD(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      COMMON/IN/PI,TI,WI,THI,EMI,GAMI,ZI
      COMMON/SHF/XSHFT,YSHFT
      COMMON/POL/ IPR,IPOLY
      COMMON/THRMAX/THRMAX
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),U(2,50)
      COMMON/C/DNUV,DNUC,XC1,YC1,XV1,YV1,DNUL
      COMMON/CAL/XC2,YC2
      COMMON/P/PINF,PTOT,TTOT
      COMMON/D3/ AZ,BZ,CZ
      COMMON/V/AV,BV,CV,XV,XV2,YV2
      COMMON/HOT/AH(3),BH(3),CH(3),XSTR,  REC,      RT,SH,IT,IVIS
      COMMON/VISF/XVTHX,YVLFT,XVMOM
      COMMON/CP/CPI,GI  ,RGAS
      COMMON/FRIC/CF(50),ST(50)
      COMMON/F/PF,TF,WF,THF,EMF,GF
      COMMON/CMTC/TTC,PTC,WC,GC,PC,THC,XNUC,ZC,EMC
      DIMENSION HOL(11),HOLE(6),DNUE(10)
      DATA HOLE/2HE0,2HE1,2HE2,2HE3,2HE4,2HE5/
      DATA HOL/2HV1,2HC1,2HA ,2HB ,2HC ,2HD ,2HV3,2HC3,2HF ,2HG ,2HV4/
   97 FORMAT(I5,8E12.4)
   98 FORMAT(/)
  100 FORMAT(8E10.0)
      D=0.
      EPS=1.E-05
      DO 23 L=1,3
      AH(L)=0.
      BH(L)=0.
   23 CH(L)=0.
      LH=1
      READ(5,100) PI,TI,WI,THI,EMI,GAMI,PINF
      READ(5,100)PF,TF,WF,THF,EMF,GF
      READ(5,100) XV1,YV1,XV2,XC1,YC1,XC2,DYV,DNUC
      READ(5,100)XF1
      READ(5,100)XTHX,YLFT,XMOM,XVTHX,YVLFT,XVMOM,XSHFT,YSHFT
      READ(5,5921) ICF,DXC,JTF,DTH,IVIS,IT
      IF(IVIS.EQ.1)READ(5,100)XSTR,REC,      SH,RT
      IF(IVIS.EQ.1.AND.IT.EQ.0)READ(5,100)AH(1),BH(1),CH(1)
 5921 FORMAT(I5,E10.0,I5,E10.0,3I5)
      XTHXI=XTHX
      YLFTI=YLFT
      XMOMI=XMOM
      XVTHXI=XVTHX
      YVLFTI=YVLFT
      XVMOMI=XVMOM
      DNUC=DNUC/57.3
      THI=THI/57.3
      DTH=DTH/57.3
      READ(5,100) AZ,BZ,CZ
      ZC1=GETZ(XC1)
      ZV1=GETZ(XV1)
      ZC2=GETZ(XC2)
      ZI=ZV1
      GI=GAMI
      WRITE(6,5922)
 5922 FORMAT(1H1////)
      WRITE(6,1020)
 1020 FORMAT(    20X*F R O Z E N   F L O W   N O Z Z L E   D E S I G N*)
```

```
      WRITE(6,5930) XV1,YV1,XV2,XC1,YC1,XC2,DYV
 5930 FORMAT(///6X*XV1*10X*YV1*10X*XV2*10X*XC1*10X*YC1*10X*XC2*10X*DYV*/
     17E13.5///)
 1800 FORMAT(*  THRUST= *E13.5,7X*LIFT = *E13.5,7X*MOMENT= *E13.5)
      WRITE(6,1800)XTHX,YLFT,XMOM
 1900 FORMAT(* VISCOUS THRUST= *E13.5,7X*VISCOUS LIFT= *E13.5,7X*
     1VISCOUS MOMENT= *E13.5)
      WRITE(6,1900)XVTHX,YVLFT,XVMOM
      WRITE(6,5923)XSHFT,YSHFT
 5923 FORMAT(9X*MOMENT AXIS*/12X*X =*E13.5/12X*Y =*E13.5///)
      WRITE(6,1001) AZ,BZ,CZ
 1001 FORMAT(9X*LATERAL EXPANSION EQUATION*/9X,22HZ(X) = AZ*X**2+BZ*X+CZ
     1/12X*AZ =*E13.5/12X*BZ =*E13.5/12X*CZ =*E13.5)
      DUM=1.+(GI-1.)/2.*EMI**2
      PTOT=PI*DUM**(GI/(GI-1.))
      TTOT=TI*DUM
      RG=49800.
      RGAS=RG/WI
      CPI=GAMI*RGAS/(GAMI-1.)
      XC22=XC2
      THC1=THI-DNUC
      DO 5000 IXC=1,ICF
      XC2=XC22+FLOAT(IXC-1)*DXC
      CALL THM(EMI,PI,GI,PINF,YV1,YC1,DYV,XV2,THRMAX,XC2,ZI)
      WRITE(6,6364) THRMAX
 6364 FORMAT(1H131X*IDEAL THRUST =*E12.4)
      YC2=YC1+TAN(THC1)*(XC2-XC1)
      YV2=YC2+DYV
      THC=ATAN((YC2-YC1)/(XC2-XC1))
      DO 6000 JT=1,JTF
      XTHX=XTHXI
      YLFT=YLFTI
      XMOM=XMOMI
      XVTHX=XVTHXI
      YVLFT=YVLFTI
      XVMOM=XVMOMI
      KSTP=50
      ISTP=50
      IEND=0
      IEXT=0
      IFLG=0
      IND=0
      THX=1.E+10
      THJT=FLOAT(JT-1)*DTH
      DNUV=ATAN((YV2-YV1)/(XV2-XV1))-THI+THJT
      WRITE(6,1894)DNUV
 1894 FORMAT(* VEHICLE EXPANSION = *E13.5)
      XV=XV1
      AV=YV1
      BV=TAN(THI+DNUV)
      CV=0.
      YF1=AV+BV*(XF1-XV)
      IDUM=DNUV*57.3
      IF(IDUM.GT.11) IDUM=11
      IF(IDUM.EQ.0) IDUM=1
      DELNU=DNUV/FLOAT(IDUM)
      IDUM=IDUM+1
      IMAX=IDUM
      KMAX=IMAX+2
      DO 10 I=1,IMAX
      X(1,I)=XV1
      Y(1,I)=YV1
      Z(1,I)=GETZ(XV1)
      TH(1,I)=THI+FLOAT(I-1)*DELNU
```

```
   10 CONTINUE
      IDUM=DNUC*57.3
      IF(IDUM.GT.11) IDUM=11
      IF(IDUM.EQ.0) IDUM=1
      DELNU=DNUC/FLOAT(IDUM)
      IDUM=IDUM+1
      X(2,1)=XC1
      Y(2,1)=YC1
      Z(2,1)=GETZ(XC1)
      ICWL=0
      I=1
      THII=THI
      XNUI=0.
   20 CONTINUE
      TH(2,1)=THII-FLOAT(I-1)*DELNU
      XNU(2,1)=FLOAT(I-1)*DELNU+XNUI
      CALL PM(2,1)
   22 CONTINUE
      K=2
   36 CONTINUE
      IF(K.LT.KMAX) GO TO 41
      IF(IEND.EQ.1)GO TO 53
      CALL VWALL(IMAX,KMAX)
      MM=K-1
      L=K-1
      IF(ICWL.EQ.1)L=K
      IF(X(2,K).LT.XV2-EPS)GO TO 24
      CALL ENDD(L,MM,KMAX)
      X(2,K)=XV2
      IF(KSTP.GE.KMAX)KSTP=KMAX
      IND=1
      GO TO 17
   24 IF(I.GT.1) GO TO 30
      AV=Y(2,KMAX)
      BV=TAN(TH(2,KMAX))
      CV=(YV2-AV-BV*(XV2-X(2,KMAX)))/(XV2-X(2,KMAX))**2
      THV2=ATAN(BV+2.*CV*(XV2-X(2,KMAX)))
      XV=X(2,KMAX)
         IF(XF1.GT.XV)YF1=AV+BV*(XF1-XV)+CV*(XF1-XV)**2
      SLE=(YF1-YC2)/(XF1-XC2)
      IF(THV2.LT.0.) GO TO 462
      DO 16 KT=2,KMAX
      XK1=XK2=XK3=XK4=0.25
      M=KT-1
      J=KT-1
      N=J
      IF(KT.EQ.KMAX)J=KT-2
      IF(KT.EQ.2.OR.KT.EQ.KMAX)N=J
      IF(KT.EQ.2.OR.KT.EQ.KMAX)XK3=0.
      IF(KT.EQ.2.OR.KT.EQ.KMAX)XK1=XK2=XK4=.333333
      CALL LTHM(X(2,M),Y(2,M),Z(2,M),X(1,N),Y(1,N),Z(1,N),X(1,J),
     1Y(1,J),Z(1,J),X(2,KT),Y(2,KT),Z(2,KT),P(2,M),P(1,N),P(1,J),
     2P(2,KT),Q(2,M),Q(1,N),Q(1,J),Q(2,KT),T(2,M),T(1,N),T(1,J),
     3T(2,KT),TH(2,M),TH(1,N),TH(1,J),TH(2,KT),XK1,XK2,XK3,XK4,1.,
     4XTHX,YLFT,XMOM,CF(M),ST(M),3)
      IF(KT.EQ.KMAX)
     ICALL LTHM(X(1,J),Y(1,J),Z(1,J),X(1,J),Y(1,J),0.,X(2,KT),Y(2,KT),0.
     2,X(2,KT),Y(2,KT),Z(2,KT),P(1,J),P(1,J),P(2,KT),P(2,KT),Q(1,J),
     3Q(1,J),Q(2,KT),Q(2,KT),T(1,J),T(1,J),T(2,KT),T(2,KT),TH(1,J),
     4TH(1,J),TH(2,KT),TH(2,KT),.25,.25,.25,.25,1.,XTHX, YLFT, XMOM,
     5CFU,STU,1)
   16 CONTINUE
      GO TO 53
   41 CONTINUE
```

```
      IF(ICWL.EQ.1.AND.K.EQ.2.AND.IEXT.EQ.1)CALL CNT
      L=K
      IF(ICWL.EQ.1)L=K+1
      IF(I.EQ.1) L   =K-1
      LM=L-1
      LL=K+ICWL-1
      IF(L   .GT.ISTP.AND.IEND.EQ.1)GO TO 30
      MM=K-1
      CALL FIX(2,K-1,1,L   ,2,K)
      IF(I.EQ.1)GO TO 30
      IF(K.GT.1)SLA=(Y(2,K)-Y(2,MM))/(X(2,K)-X(2,MM))
      CALL GEM(X(2,MM),Y(2,MM),SLA,XC2,YC2,SLE,XC,YC)
      IF(XC.GE.X(2,K)  .OR.XC.LT.X(2,MM)-EPS)GO TO 30
      KSTP=K
      WRITE(6,88)KSTP,ISTP,KMAX,IMAX
   88 FORMAT(1X,4I5)
   30 CONTINUE
      LM=L-1
      IF(I.EQ.1)GO TO33
      IF(IEXT.EQ.1)GO TO 32
      IF(ICWL.EQ.0.OR.K.GT.2)GO TO 32
      CALL LTHM(X(1,1),Y(1,1),Z(1,1),X(2,1),Y(2,1),Z(2,1),X(2,1),
     1Y(2,1),0.,X(1,1),Y(1,1),0.,P(1,1),P(2,1),P(2,1),P(1,1),Q(1,1),
     2Q(2,1),Q(2,1),Q(1,1),T(1,1),T(2,1),T(2,1),T(1,1),TH(1,1),TH(2,1),
     3TH(2,1),TH(1,1),.25,.25,.25,.25,1.,XTHX, YLFT, XMOM,CFL,STL,2)
      CALL LTHM(X(1,1),Y(1,1),Z(1,1),X(1,2),Y(1,2),Z(1,2),X(2,1),Y(2,1),
     1Z(2,1),X(2,1),Y(2,1),Z(2,1),P(1,1),P(1,2),P(2,1),P(2,1),Q(1,1),
     2Q(1,2),Q(2,1),Q(2,1),T(1,1),T(1,2),T(2,1),T(2,1),TH(1,1),TH(1,2),
     3TH(2,1),TH(2,1),.33333,.33333,.33333,0.,1.,XTHX, YLFT, XMOM,
     4CF(1),ST(1),3)
   32 CONTINUE
      XK1=XK2=XK3=XK4=.25
      IF(IEND.EQ.0.AND.K.EQ.KMAX)GO TO 17
      AVG=4.
      SLB=(Y(2,K)-Y(1,L))/(X(2,K)-X(1,L))
      CALL GEM(X(1,L),Y(1,L),SLB,XC2,YC2,SLE,XC,YC)
      RAT=(XC- X(1,L))/(X(2,K)-X(1,L))
      IF(RAT.GT.0.99)GO TO 144
      IF(RAT.GT.0.)GO TO 143
      AVG=2.
      GO TO 144
  143 AVG=AVG-1.
  144 CONTINUE
      IF((X(2,MM)-X(1,LM)).EQ.0.)GOTO 148
      SLB=(Y(2,MM)-Y(1,LM))/(X(2,MM)-X(1,LM))
      CALL GEM(X(1,LM),Y(1,LM),SLB,XC2,YC2,SLE,XC,YC)
      RAT =(XC-X(1,LM))/(X(2,MM)-X(1,LM))
      IF(RAT.GT.0.99)GO TO 148
      IF(RAT.GT.0.)GO TO 145
      AVG=AVG-2.
      GO TO 148
  145 AVG=AVG-1.
  148 CONTINUE
      AVG=AVG/4.
      CALL LTHM(X(2,MM),Y(2,MM),Z(2,MM),X(1,LM),Y(1,LM),Z(1,LM),X(1,L),
     1Y(1,L),Z(1,L),X(2,K),Y(2,K),Z(2,K),P(2,MM),P(1,LM),P(1,L),P(2,K),
     2Q(2,MM),Q(1,LM),Q(1,L),Q(2,K),T(2,MM),T(1,LM),T(1,L),T(2,K),
     3TH(2,MM),TH(1,LM),TH(1,L),TH(2,K),XK1,XK2,XK3,XK4,AVG,XTHX, YLFT,
     4XMOM,CF(LL),ST(LL),3)
      IF(IEND.EQ.1.OR.K.LT.KMAX)GO TO 33
   17 CONTINUE
      M=K-1
      L=M
      IF(ICWL.EQ.1)L=K
```

```
      CALL GEM(X(2,M),Y(2,M),SLA,XC2,YL2,SLE,XC,YC)
      RAT=(XC-X(2,M))/(X(2,K)-X(2,M))
      IF(RAT.GT.0.99)GO TO 177
      AVG=AVG-1.
  177 SLB=(Y(2,M)-Y(1,L))/(X(2,M)-X(1,L))
      CALL GEM(X(1,L),Y(1,L),SLB,XC2,YC2,SLE,XC,YC)
      RAT=(XC-X(1,L))/(X(2,M)-X(1,L))
      IF(RAT.GT.0.99)GO TO 178
      IF(RAT.GT.0.)GO TO 173
      AVG=AVG-2.
  173 AVG=AVG-1.
  178 CONTINUE
      AVG=AVG/3.
      CALL LTHM(X(2,M),Y(2,M),Z(2,M),X(1,L),Y(1,L),Z(1,L),X(2,K),Y(2,K),
     1Z(2,K),X(2,K),Y(2,K),Z(2,K),P(2,M),P(1,L),P(2,K),P(2,K),Q(2,M),
     2Q(1,L),Q(2,K),Q(2,K),T(2,M),T(1,L),T(2,K),T(2,K),TH(2,M),TH(1,L),
     3TH(2,K),TH(2,K),.33333,.33333,.33333,0.,AVG,XTHX, YLFT, XMOM,
     4CF(LL),ST(LL),3)
   43 CALL LTHM(X(1,L),Y(1,L),Z(1,L),X(1,L),Y(1,L),0.,X(2,K),Y(2,K),
     10.,X(2,K),Y(2,K),Z(2,K),P(1,L),P(1,L),P(2,K),P(2,K),Q(1,L),Q(1,L),
     2Q(2,K),Q(2,K),T(1,L),T(1,L),T(2,K),T(2,K),TH(1,L),TH(1,L),TH(2,K),
     3TH(2,K),.25,.25,.25,.25,1.,XTHX, YLFT, XMOM,CFU,STU,1)
   33 IF(IEND.EQ.1)KMAX=ISTP
      K=K+1
      IF(K.LE.KMAX)GO TO 36
   53 KP=KMAX
      IF(IEND.EQ.1)KP=KMAX-1-ICWL
      IF(IND.EQ.1)IEND=1
      IND=0
      WRITE(6,6885)
 6885 FORMAT(1X*PT.*6X*X*11X*Y*8X*PRESSURE*5X*ANGLE*8X*MACH*4X*TEMPERATU
     1RE*1X*PM FUNCTION*3X*VELOCITY*)
      DO 50 L=1,KP
      WRITE(6,97) L,X(2,L),Y(2, L),P(2,L),TH(2,L),EM(2,L),T(2,L),XNU(2,
     1L),Q(2,L)
   50 CALL SWITCH(2,L,1,L)
      WRITE(6,2001)CFU,STU,CFL,STL
 2001 FORMAT(* VEH. FRIC. COFF= *E13.5,2X*VEH. STANTON NUM.= *E13.5,2X*
     1COWL FRIC. COEF.= *E13.5,2X*COWL STANTON NUM.= *E13.5)
      WRITE(6,450)
      NPR1=IMAX/5
      DO 166 K=1,NPR1
      K1=K$K2=K1+NPR1$K3=K2+NPR1$K4=K3+NPR1$K5=K4+NPR1
      KDONE=K5
      WRITE(6,500)CF(K1),ST(K1),CF(K2),ST(K2),CF(K3),ST(K3),
     1CF(K4),ST(K4),CF(K5),ST(K5)
  166 CONTINUE
      IF(KDONE.EQ.IMAX)GO TO  55
      NPR2=5*NPR1+1
      DO 414 K=NPR2,IMAX
      WRITE(6,550)CF(K),ST(K)
  414 CONTINUE
   55 CONTINUE
  450 FORMAT(1X,5(6X,*CF  *,9X,* ST   *,3X))
  500 FORMAT(1X,10E13.5)
  550 FORMAT(105X,2E13.5)
      WRITE(6,98)
      WRITE(6,1800)XTHX,YLFT,XMOM
      WRITE(6,1900)XVTHX,YVLFT,XVMOM
      IMAX=KMAX
      I=I+1
      IF(I.GT.IDUM)ICWL=1
      IF(ICWL.EQ.0)KMAX=KMAX+1
```

```
      IF(IEXT.EQ.0.AND.X(1,1).GE.XC2-EPS)GO TO 5900
      IF(ICWL.EQ.1)GO TO 22
      GO TO 20
  462 CONTINUE
      WRITE(6,992)
  992 FORMAT(*THV2.LT.0*)
      GO TO 6000
 5900 CONTINUE
      IF(P(1,1).LE.PF)GO TO 5396
      CALL COWL(DNUE)
      IDUM=6
      I=2
      XNUI=XNU(1,1)
      THII=TH(1,1)
      ICWL=0
      KMAX=KMAX+1
      DELNU=DNUE/FLOAT(IDUM)
      IDUM=IDUM+1
      IEXT=1
      GO TO 20
 5396 CONTINUE
 6000 CONTINUE
 5000 CONTINUE
      END
```

```
      SUBROUTINE CWALL(IMAX,KMAX,KSTP,ISTP)
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50)
      COMMON/C/DNUV,DNUC,XC1,YC1,XV1,YV1,DMUL
      COMMON/CAL/XC2,YC2
      D=0.
      IADD=0
      LOOP=0
      XTHM1=TH(1,1)-XMU(1,1)
      Q1=XNU(1,1)-TH(1,1)
      CALL INT(0.,X(1,2),Y(1,2),Z(1,2),TH(1,2),XNU(1,2),P(1,2),T(1,2),
     1EM(1,2),XMU(1,2),D,D,D,D,D,D,D,D,D,XA,YA,ZA,THA,XNUA,PA,TA,
     2EMA,XMUA,-1.)
      Q2=XNU(1,2)-TH(1,2)
   44 XTHM2=THA-XMUA
      IF(LOOP.EQ.0)XTHM3=XTHM2
      SLA=(TAN(XTHM2)+TAN(XTHM3))/2.
      SLB=(YC2-YC1)/(XC2-XC1)
      CALL GEM(XA     ,YA     ,SLA,XC2,YC2,SLB,XC,YC)
      IF(XC.LE.XC2)GO TO 43
      IADD=1
      DX=X(1,2)-X(1,1)
      SLU=(Y(1,2)-Y(1,1))/DX
      IT=1
      XA=(X(1,2)+X(1,1))/2.
   24 RAT=(XA-X(1,1))/DX
      SLB=XTHM1+RAT*(XTHM2-XTHM1)
      SLB=TAN(SLB)
      IF(LOOP.EQ.1)SLB=(SLB+TAN(XTHM3))/2.
      CALL GEM(X(1,1),Y(1,1),SLU,XC2,YC2,SLB,XAT,YA)
      ER=ABS((XA-XAT)/DX)
      IF(ER.LT.1.E-04)GO TO 63
      IT=IT+1
      IF(IT.GT.10)GO TO 68
      XA=XAT
      GO TO 24
   68 WRITE(6,38)
   38 FORMAT(* TOO MANY ITER IN CWALL *)
      WRITE(6,39)LOOP,SLU,SLB,XA,XAT
   39 FORMAT(1X,I5,5E13.5)
      STOP
   63 CONTINUE
      XC=XC2
      YC=YC2
      IM=IMAX+1
      X(1,IM)=XA
      Y(1,IM)=YA
      Z(1,IM)=GETZ(XA)
      XNU(1,IM)=XNU(1,1)+RAT*(XNU(1,2)-XNU(1,1))
      QA=Q1+RAT*(Q2-Q1)
      TH(1,IM)=XNU(1,IM)-QA
      CALL PM(1,IM)
      CALL INT(0.,X(1,IM),Y(1,IM),Z(1,IM),TH(1,IM),XNU(1,IM),P(1,IM),
     1T(1,IM),EM(1,IM),XMU(1,IM),D,D,D,D,D,D,D,D,D,XA,YA,ZA,THA,XNUA,
     2PA,TA,EMA,XMUA,1.)
   43 RA=THA+XNUA
      IF(ABS(XC2-XC).LE..0001)XC=XC2
      X(2,1)=XC
      Y(2,1)=YC
```

```
      CALL PM(2,1)
      XTHM3=TH(2,1)-XMU(2,1)
      IF(LOOP.EQ.1)GO TO 6
      LOOP=1
      GO TO 44
    6 IF(IADD.EQ.0)RETURN
      IMAX=IMAX+1
      KMAX=KMAX+1
      KSTP=KSTP+1
      ISTP=ISTP+1
      DO 46 JJ=3,IMAX
      LJ=IMAX-JJ+3
      LI=LJ-1
   46 CALL SWITCH(1,LI,1,LJ)
      WRITE(6,181)IADD,XA,X(1,1),X(1,2)
  181 FORMAT(1X,I5,3E13.5)
      CALL INT(0.,XA,YA,ZA,THA,XNUA,PA,TA,EMA,XMUA,D,D,D,D,D,D,D,D,D,
     1X(1,2),Y(1,2),Z(1,2),TH(1,2),XNU(1,3),P(1,2),T(1,2),EM(1,2),
     2XMU(1,2),-1.)
      RETURN
      END
```

```
      SUBROUTINE ENDO(L,KK,K6)
      COMMON/V/AV,BV,CV,XV,XV2,YV2
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50)
      IT=1
      B=0.
      A=1.
      XM1=TH(1,L )+XMU(1,L )
      XM2=TH(2,KK)+XMU(2,KK)
      XM3=0.
      Q1=TH(1,L )+XNU(1,L )
      Q2=TH(2,KK)+XNU(2,KK)
      XA=(X(1,L )+X(2,KK))/2.
      DX=X(2,KK)-X(1,L )
      SLM=(Y(2,KK)-Y(1,L ))/DX
   12 RAT=(XA-X(1,L ))/DX
      SLP=XM1+RAT*(XM2-XM1)
      SLP=A*SLP+B*XM3
      CALL GEM(X(1,L ),Y(1,L ),SLM,XV2,YV2,SLP,XAT,YA)
      ER=ABS((XA-XAT) /DX)
      IF(ER.LT.1.E-03)GO TO 14
      IT=IT+1
      IF(IT.LE.10)GO TO 8
      WRITE(6,33)
   33 FORMAT(* TOO MANY ITER IN END *)
      WRITE(6,34)L,KK,K6,XA,XAT,X(2,KK),X(1,L),SLP,XM3
   34 FORMAT(1X,3I5,6E13.5)
      STOP
    8 XA=XAT
      GO TO 12
   14 QA=Q1+RAT*(Q2-Q1)
      TH(1,L +2)=TH(1,L )+RAT*(TH(2,KK)-TH(1,L ))
      XNU(1,L +2)=QA-TH(1,L +2)
      Z(1,L +2)=GETZ(XA)
      CALL PM(1,        L +2)
      RA=XNU(1,L +2)-TH(1,L +2)
      X(2,K6)=XV2
      Y(2,K6)=YV2
      Z(2,K6)=GETZ(XV2)
      TH(2,K6)=ATAN (BV+2.*CV*(XV2-XV))
      XNU(2,K6)=RA+TH(2,K6)
      CALL PM(2,K6)
      IEND=1
      IF(B.GT.0.)RETURN
      IT=1
      B=.5
      A=.5
      XM3=TH(2,K6)+XMU(2,K6)
      GO TO 12
      END
```

```
      SUBROUTINE INT(RAT,X1,Y1,Z1,TH1,XNU1,P1,T1,EM1,XMU1,
     1X2,Y2,Z2,TH2,XNU2,P2,T2,EM2,XMU2,X3,Y3,Z3,TH3,XNU3,P3,T3,
     2EM3,XMU3,OPT)
      Q1=XNU1+OPT*TH1
      Q2=XNU2+OPT*TH2
      X3=X1+RAT*(X2-X1)
      Y3=Y1+RAT*(Y2-Y1)
      Q3=Q1+RAT*(Q2-Q1)
      P3=P1+RAT*(P2-P1)
      T3=T1+RAT*(T2-T1)
      EM3=EM1+RAT*(EM2-EM1)
      XNU3=XNU1+RAT*(XNU2-XNU1)
      TH3=(Q3-XNU3)/OPT
      XMU3=ASIN(1./EM3)
      Z3=GETZ(X3)
      RETURN
      END
```

```
      SUBROUTINE THM(EM1,P1,G,PINF,YV1,YC1,DYV,XV2,THRMAX,XC2,ZI)
      A1=YV1-YC1
      A1=A1*ZI
      Z1=GETZ(XV2)
      Z2=GETZ(XC2)
      A2=DYV*(Z1+Z2)/2.
      FM1=1.+(G-1.)/2.*EM1**2
      DUM=(2.*FM1/(G+1.))**((G+1.)/2./(G-1.))
      AST=A1*EM1/DUM
      PTOT=P1/FM1**(G/(1.-G))
      EM2=EM1*SQRT(A2/A1)
      IF(EM1.GT.3.)EM2=(A2/A1)**.3*EM1
      AF=A2/AST
      ITM=0
   10 CONTINUE
      FM2=1.+(G-1.)/2.*EM2**2
      DUM=(2.*FM2/(G+1.))**((G+1.)/2./(G-1.))
      AFT=DUM/EM2
      ERA=(AFT-AF)/AF
      IF(ABS(ERA).LT.1.E-03) GO TO 20
      CALL ERROR(2000,ITM,EM2,ERA,1.1,EM21,ERA1)
      GO TO 10
   20 CONTINUE
      F1=P1*A1*(1.+G*EM1**2)
      P2=FM2**(G/(1.-G))*PTOT
      F2=P2*A2*(1.+G*EM2**2)
      THRMAX=F2-F1-PINF*(A2-A1)
      RETURN
      END
```

```
      SUBROUTINE EM3D(EM,EMX,X,G,Z,ZI)
      GN=(G+1.)/(G-1.)/2.
      Y=(1.+(G-1.)/2.*EM*EM)**GN
      Y=Y/EM/((G+1.)/2.)**GN
      A=Y*Z/ZI
      EMX=EM*SQRT(Z)
      ITM=1
   10 AT=(1.+(G-1.)/2.*EMX*EMX)**GN
      AT=AT/EMX/((G+1.)/2.)**GN
      ERM=(AT-A)/A
      IF(ABS(ERM).LT.1.E-03) GO TO 20
      CALL ERROR(10, ITM,EMX,ERM,1.1,EMX1,ERM1)
      GO TO 10
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SWITCH(I2,K,I1,L)
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50)
      X  (I1,L)=X  (I2,K)
      Y  (I1,L)=Y  (I2,K)
      Z  (I1,L)=Z  (I2,K)
      TH (I1,L)=TH (I2,K)
      XNU(I1,L)=XNU(I2,K)
      P  (I1,L)=P  (I2,K)
      T  (I1,L)=T  (I2,K)
      EM (I1,L)=EM (I2,K)
      XMU(I1,L)=XMU(I2,K)
      Q(I1,L)=Q(I2,K)
      RETURN
      END
```

```
      FUNCTION GETZ(X)
      COMMON/D3/ AZ,BZ,CZ
      GETZ=AZ*X**2+BZ*X+CZ
      RETURN
      END
```

```
      SUBROUTINE VWALL (IMAX,KMAX)
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50)
      COMMON/V/AV,BV,CV,XV,XV2,YV2
      COMMON/C/DNUV,DNUC,XC1,YC1,XV1,YV1,DNUL
      IBEG=0
      ITW=1
      SL2=TH(1,IMAX)
      SL1=TAN(TH(2,KMAX-1)+XMU(2,KMAX-1))
      SL13=SL1
      CALL GEM(X(2,KMAX-1),Y(2,KMAX-1),SL1,X(1,IMAX),Y(1,IMAX),SL2,
     1XG,YG)
   12 YW=AV+BV*(XG-XV)+CV*(XG-XV)**2
      ERW=(YW-YG)/(YV1-YC1)
      IF(ABS(ERW).LT.1.E-02) GO TO  10
      CALL ERROR(1,ITW,XG,ERW,.9,XC1,ERW1)
      YG=Y(2,KMAX-1)+SL13*(XG-X(2,KMAX-1))
   10 TH(2,KMAX)=ATAN(BV+2.*CV*(XG-XV))
      XNU(2,KMAX)=TH(2,KMAX)-TH(2,KMAX-1)+XNU(2,KMAX-1)
      X(2,KMAX)=XG
      Y(2,KMAX)=YG
      Z(2,KMAX)=GETZ(XG)
      CALL PM(2,KMAX)
      IF(IBEG.EQ.1) RETURN
      IBEG=1
      SL13=.5*(SL1+TAN(TH(2,KMAX)+XMU(2,KMAX)))
      GO TO 12
      END
```

```
      SUBROUTINE GEM(XA,YA,SLA,XB,YB,SLB,XC,YC)
      XC=(YB-YA+SLA*XA-SLB*XB)/(SLA-SLB)
      YC=YA+SLA*(XC-XA)
      RETURN
      END
```

```
      SUBROUTINE ERROR (I,IT,X,ER,F,X1,ER1)
      IT=IT+1
      IF(IT.LT.15) GO TO 12
      WRITE(6,13)
   13 FORMAT(*ERROR TEST NUMBER *)
      WRITE (6,20) I
   20 FORMAT(I5)
      STOP
   12 IF(IT.GT.2) GO TO 14
      ER1=ER
      X1=X
      X=X*F
      IF(X.EQ.X1) X=X+.02
      RETURN
   14 XD=X1-ER1*(X-X1)/(ER-ER1)
      ER1=ER
      X1=X
      X=XD
      RETURN
      END
```

```
      SUBROUTINE FIX(I1,K1,I2,K2,I3,K3)
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),W(2,50)
      DUM3=0.
      DUM4=0.
      A=1.
      B=0.
      DUM1=TAN(TH(I1,K1)+XMU(I1,K1))
      DUM2=TAN(TH(I2,K2)-XMU(I2,K2))
   10 IF(B.GT.0.) DUM3=TAN(TH(I3,K3)+XMU(I3,K3))
      IF(B.GT.0.) DUM4=TAN(TH(I3,K3)-XMU(I3,K3))
      SL1=A*DUM1+B*DUM3
      SL2=A*DUM2+B*DUM4
      CALL GEM(X(I1,K1),Y(I1,K1),SL1,X(I2,K2),Y(I2,K2),SL2,X(I3,K3),
     1Y(I3,K3))
      Z(I3,K3)=GETZ(X(I3,K3))
      XNU(I3,K3)=.5*(XNU(I1,K1)+XNU(I2,K2)+TH(I2,K2)-TH(I1,K1))
      TH(I3,K3)=.5*(XNU(I2,K2)-XNU(I1,K1)+TH(I2,K2)+TH(I1,K1))
      CALL PM(I3,K3)
      IF(B.GT.0.) RETURN
      A=.5
      B=.5
      GO TO 10
      END
```

```
      SUBROUTINE PM(IX,KX)
      COMMON/IN/PI,TI,NI,THI,EMI,GAMI,ZI
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50)
      COMMON/P/PINF,PTOT,TTOT
      COMMON/CP/CPI,GI   ,RGAS
      DNU=XNU(IX,KX)
      G=GI
      EM1=EMI
      GG=SQRT((G+1.)/(G-1.))
      XM1=SQRT(EM1**2-1.)
      XNU1=GG*ATAN(XM1/GG)-ATAN(XM1)
      EM2=DNU/(1.5-XNU1)*(6.-EM1)+EM1
      IT3=1
   10 XM2=SQRT(EM2**2-1.)
      DNUT=GG*(ATAN(XM2/GG)-ATAN(XM1/GG))+ATAN(XM1)-ATAN(XM2)
      ERNU=DNU-DNUT
      IF(ABS(ERNU).LT.1.E-04) GO TO 20
      CALL ERROR(3,IT3,EM2,ERNU,1.)1,EM21,ERNU1)
      GO TO 10
   20 CONTINUE
      CALL EM3D(EM2,EMX,X(IX,KX),G,Z (IX,KX),ZI)
      P(IX,KX)=PTOT/(1.+(G-1.)/2.*EMX**2)**(G/(G-1.))
      T(IX,KX)=TTOT/(1.+(G-1.)/2.*EMX**2)
      EM(IX,KX)=EMX
      XMU(IX,KX)=ASIN(1./EMX)
      AX=SQRT(G*RGAS*T(IX,KX))
      Q(IX,KX)=EMX*AX
      RETURN
      END
```

```
      SUBROUTINE GNURE(RH,G,P,T,R,          X,X1,CF,ST,L)
      COMMON/CP/CPI,GI   ,RGAS
      COMMON/HOT/AH(3),BH(3),CH(3),XSTR,  REC,       RT,SH,IT,IVIS
      HDEL=R-G*Q/2.
      HAW=1.+REC*3*Q/2./HDEL
      IF(IT .EQ.0)TW=AH(L)*(X-X1)**2+BH(L)*(X-X1)+CH(L)
      IF(IT .EQ.1)GO TO 46
      HW=CPI*TW
      HW=HW/HDEL
      GO TO 48
   46 HW=HAW
   48 A=HAW-1.
      B=HW-1.
      C=SQRT((A+B)**2+4.*A)
      FC=A/(ASIN((A-B)/C)+ASIN((A+B)/C))**2
      FRX=HAW**(.7/2)/(FC*(HW)**(1.474))
      CALL VIS(T,XMMU)
      REX=RH*Q*(X+XSTR)*RT /XMMU
      REXI=FRX*REX
      CFI=.088*(ALOG10(REXI)-2.3686)/(ALOG10(REXI)-1.5)**3
      CF=CFI/FC
      ST=CF*SH/2.
      RETURN
      END
```

```
      SUBROUTINE VIS(T,XMUU)
      XMUU=2.27*T**1.5*1.E-08/(T+198.6)
      RETURN
      END
```

```
      SUBROUTINE SNARF(X1,Y1,Z1,X2,Y2,Z2,X3,Y3,Z3,X4,Y4,Z4,AVX,AVY,AVZ,
     1XNX,XNY,XNZ,AS,XO,YO,ZO,LH)
      DIMENSION XPA(4),YPA(4),ZPA(4),XI(4),ETA(4)
      XPA(1)=X1
      YPA(1)=Y1
      ZPA(1)=Z1
      ZPA(2)=Z2
      YPA(2)=Y2
      XPA(2)=X2
      XPA(3)=X3
      YPA(3)=Y3
      ZPA(3)=Z3
      ZPA(4)=Z4
      YPA(4)=Y4
      XPA(4)=X4
      T1X=X3-X1
      T1Y=Y3-Y1
      T1Z=Z3-Z1
      T2X=X4-X2
      T2Y=Y4-Y2
      T2Z=Z4-Z2
      XNX=T2Y*T1Z-T1Y*T2Z
      XNY=T1X*T2Z-T2X*T1Z
      XNZ=T2X*T1Y-T1X*T2Y
      VN=SQRT(XNX**2+XNY**2+XNZ**2)
      IF(VN.LE.1.E-13)GO TO 6
      XNX=XNX/VN
      XNY=XNY/VN
      XNZ=XNZ/VN
      D=XNX*(AVX-X1)+XNY*(AVY-Y1)+XNZ*(AVZ-Z1)
      PD=ABS(D)
      T=SQRT(T1X*T1X+T1Y*T1Y+T1Z*T1Z)
      T1X=T1X/T
      T1Y=T1Y/T
      T1Z=T1Z/T
      T2X=XNY*T1Z-XNZ*T1Y
      T2Y=XNZ*T1X-XNX*T1Z
      T2Z=XNX*T1Y-XNY*T1X
      DO 1000 J=1,4
      XPA(J)=XPA(J)+XNX*D
      YPA(J)=YPA(J)+XNY*D
      ZPA(J)=ZPA(J)+XNZ*D
      D=-D
      XDIF=XPA(J)-AVX
      YDIF=YPA(J)-AVY
      ZDIF=ZPA(J)-AVZ
      XI(J)=T1X*XDIF+T1Y*YDIF+T1Z*ZDIF
 1000 ETA(J)=T2X*XDIF+T2Y*YDIF+T2Z*ZDIF
      XIO=(XI(4)*(ETA(1)-ETA(2))+XI(2)*(ETA(4)-ETA(1)))/(ETA(2)-ETA(4))
     1/3.
      ETAO=-ETA(1)/3.
      DO 1020 J=1,4
      XI(J)=XI(J)-XIO
 1020 ETA(J)=ETA(J)-ETAO
      XO=AVX+T1X*XIO+T2X*ETAO
      YO=AVY+T1Y*XIO+T2Y*ETAO
      ZO=AVZ+T1Z*XIO+T2Z*ETAO
      AS=(ETA(2)-ETA(4))*(XI(3)-XI(1))/2.
      AS=ABS(AS)
```

```
      AS=0.
      RETURN
      END
      SUBROUTINE LTH4(X1,Y1,Z1,X2,Y2,Z2,X3,Y3,Z3,X4,Y4,Z4,P1,P2,P3,P4,
     1Q1,Q2,Q3,Q4,T1,T2,T3,T4,TH1,TH2,TH3,TH4,XK1,XK2,XK3,XK4,AVG,
     2XXTHX,XYLFT,XXMOM,CFF,ST,LH)
      COMMON/P/PINF,PTOT,TTOT
      COMMON/CP/CPI,GI   ,RGAS
      COMMON/SHF/XSHFT,YSHFT
      COMMON/HOT/AH(3),BH(3),CH(3),XSTR,   REC,        RT,SH,IT,IVIS
      COMMON/VISF/XVTHX,YVLFT,XVMOM
      P=XK1*P1+XK2*P2+XK3*P3+XK4*P4
      Q=XK1*Q1+XK2*Q2+XK3*Q3+XK4*Q4
      T=XK1*T1+XK2*T2+XK3*T3+XK4*T4
      TH=XK1*TH1+XK2*TH2+XK3*TH3+XK4*TH4
      RH=P/RGAS/T
      R=CPI*T+Q*Q/2.
      AVX=XK1*X1+XK2*X2+XK3*X3+XK4*X4
      AVY=XK1*Y1+XK2*Y2+XK3*Y3+XK4*Y4
      AVZ=XK1*Z1+XK2*Z2+XK3*Z3+XK4*Z4
      CALL SNARF(X1,Y1,Z1,X2,Y2,Z2,X3,Y3,Z3,X4,Y4,Z4,AVX,AVY,AVZ,XNX,
     1XNY,XNZ,ASS,X0,Y0,Z0,LH)
      CFF=0.
      XBP=0.
      IF(IVIS.EQ.1)CALL GNURE(RH,Q,P,T,R,          X0,XBP,CFF,ST,1 )
      RHQ=RH*Q*Q/2.
      PAV=P-PINF
      DXTHX=-PAV*XNX*ASS
      DYLFT= PAV*XNY*ASS
      XNZZ=1.
      IF(LH.EQ.3)XNZZ=XNZ
      DXTHXV=-CFF              *COS(TH)*ASS*RHQ
      DYLFTV=CFF        *SIN(TH)*ASS*RHQ
      DXTHXV=DXTHXV*AVG
      DYLFTV=DYLFTV*AVG
      XMS=X0-XSHFT
      YMS=Y0-YSHFT
      DMOMV=YMS*DXTHXV+XMS*DYLFTV
      XVTHX=XVTHX+DXTHXV
      YVLFT=YVLFT+DYLFTV
      XVMOM=XVMOM+DMOMV
      DXTHX=DXTHX*AVG+DXTHXV
      DYLFT=DYLFT*AVG+DYLFTV
      DMOM=YMS*DXTHX+XMS*DYLFT
      XXTHX=XXTHX+DXTHX
      XYLFT=XYLFT+DYLFT
      XXMOM=XXMOM+DMOM
      RETURN
      END
```

```
      SUBROUTINE CNT
      COMMON/IN/PI,TI,WI,THI,EMI,GAMI,ZI
      COMMON/CNTC/TTC,PTC,WC,GC,PC,THC,XNUC,ZC,EMC
      COMMON/P/PINF,PTOT,TTOT
      COMMON/CP/CPI,GI  ,RGAS
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50)
      A=1. $ B=0.
      TOTS=TTOT $ POTS=PTOT $ GIS=GI $ZIS=ZI$EMIS=EMI
      IT=1
      RB=XNU(1,2)+TH(1,2)
      TH(2,1)=TH(1,1)
   20 SLA=A*TAN(TH(2,1))+B*TAN(TH(1,1))
      SLB=TH(1,2)-XMU(1,2)
      SLB=A*TAN(SLB)
      IF(B.GT.0.)SLB=SLB+B*TAN(TH(2,1)-XMU(2,1))
      CALL GEM(X(1,2),Y(1,2),SLB,X(1,1),Y(1,1),SLA,X(2,1),Y(2,1))
      Z(2,1)=GETZ(X(2,1))
      XNU(2,1)=RB-TH(2,1)
      CALL PM(2,1)
      TTOT=TTC $ PTOT=PTC $ GI=GC $ZI=ZC $EMI=EMC
      RC=XNUC-THC
      TH(2,2)=TH(2,1)
      XNU(2,2)=RC+TH(2,2)
      X(2,2)=X(2,1)
      Y(2,2)=Y(2,1)
      Z(2,2)=GETZ(X(2,2))
      CALL PM(2,2)
      ER3=(P(2,1)-P(2,2))/PC
      IF(ABS(ER3).LT.1.E-04)GO TO 16
      CALL ERROR(IER,IT,TH(2,1),ER3,1.01,TH23,ER23)
      TTOT=TOTS $ PTOT=POTS $ GI=GIS $ZI=ZIS $EMI=EMIS
      GO TO 20
   16 CONTINUE
      TTOT=TOTS $ PTOT=POTS $ GI=GIS $ZI=ZIS $EMI=EMIS
      IF(B.GT.0.)RETURN
      IT=1
      A=.5 $ B=.5
      GO TO 20
      END
```

```
      SUBROUTINE COWL(DNUE)
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50)
      COMMON/CAL/XC2,YC2
      COMMON/P/PINF,PTOT,TTOT
      COMMON/F/PF,TF,WF,THF,EMF,GF
      COMMON/CP/CPI,GI    ,RGAS
      COMMON/CNTC/TTC,PTC,WC,GC,PC,THC,XNUC,ZC,EMC
      PCC=(PF+P(1,1))/2.
      GM1=GF-1.
      GP1=GF+1.
      EMF2=EMF*EMF
      DUM=1.+GM1*EMF2/2.
      PTF=PF*DUM**(GF/GM1)
      TTF=TF*DUM
      TOTS=TTOT $POTS=PTOT $GIS=GI
      XMUF=ASIN(1./EMF)
      IT=1
      BET=(THF-XMUF+TH(1,1))*1.1-THF
   20 DUM=(EMF*SIN(BET))**2
      PC=(2.*GF*DUM-GM1)/GP1
      TC=PC*(GM1*DUM+2.)/DUM/GP1
      EMC=(EMF2*(GP1*PC+GM1)-2.*(PC*PC-1.))/(GM1*PC+GP1)/PC
      EMC=SQRT(EMC)
      PC=PC*PF
      THC=TAN(BET)*(GP1*EMF2/(DUM-1.)/2.-1.)
      THC=ATAN(1./THC)+THF
      PTC=(2.*TC/(GM1*EMF2+2.))**(GF/GM1)
      PTC=PC/PTC
      TTC=TTF
      TC=TC*TF
      RA=XNU(1,1)+TH(1,1)
      X(2,1)=XC2 $Y(2,1)=YC2 $TH(2,1)=THC
      Z(2,1)=GETZ(XC2)
      XNU(2,1)=RA-TH(2,1)
      CALL PM(2,1)
      ER4=(PC-P(2,1))/PCC
      IF(ABS(ER4).LT.1.E-04)GO TO 16
      CALL ERROR(4,IT,BET,ER4,1.05,BET1,ER41)
      GO TO 20
   16 DNUE=ABS(XNU(2,1)-XMU(1,1))
      TTOT=TOTS $PTOT=POTS $GI=GIS
      WC=WF
      GC=GF
      ZC=Z(2,1)
      XNUC=0.
      RETURN
      END
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
#
850.        2000.       28.96       0.          3.          1.4         23.1
23.09       418.8       28.97       0.          10.         1.4
0.          1.          15.         0.          0.          5.          6.          10.
15.
0.          0.          0.          0.          0.          0.          0.          .5
     1      1.          1           1.          1           1
0.          1.          1.          1.
0.          0.          1.
```

APPENDIX III

LISTING OF EQUILIBRIUM FLOW PROGRAM

```
      PROGRAM NOZOE(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      COMMON/IN/PI,TI,WI,THI,EMI,GI,ZI,HI,RHI,UI
      COMMON/SHF/XSHFT,YSHFT
      COMMON/THRMAX/THRMAX
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50),H(2,50),RH(2,50),
     2G(2,50)
      COMMON/D/PHI1
      COMMON/HOT/AH(3),BH(3),CH(3),XSTR,  REC,       RT,SH,IT,IVIS
      COMMON/C/DNUV,DNUC,XC1,YC1,XV1,YV1,DNUL
      COMMON/CWL/XC2,YC2
      COMMON/P/PINF,PTOT,TTOT
      COMMON/D3/ AZ,BZ,CZ
      COMMON/V/AV,BV,CV,XV,XV2,YV2
      COMMON/VISF/XVTHX,YVLFT,XVMOM
      COMMON/CP/CPI,      RGAS
      COMMON/FRIC/CF(50),ST(50)
      COMMON/F/PF,TF,WF,THF,EMF,GF
      COMMON/CNTC/TTC,PTC,WC,GC,PC,THC,XNUC,ZC,EMC
      DIMENSION HOL(11),HOLE(6),DNUE(10)
      DATA HOLE/2HE0,2HE1,2HE2,2HE3,2HE4,2HE5/
      DATA HOL/2HV1,2HC1,2HA ,2HB ,2HC ,2HD ,2HV3,2HC3,2HF ,2HG ,2HV4/
   97 FORMAT(I5,8E12.4)
   98 FORMAT(/)
  100 FORMAT(8E10.0)
      D=0.
      EPS=1.E-05
      DO 23 L=1,3
      AH(L)=0.
      BH(L)=0.
   23 CH(L)=0.
      LH=1
      READ(5,100) PI,TI,WI,THI,EMI,PINF
      READ(5,100)PF,TF,WF,THF,EMF,GF
      READ(5,100) XV1,YV1,XV2,XC1,YC1,XC2,DYV,DNUC
      READ(5,100)XF1
      READ(5,100)XTHX,YLFT,XMOM,XVTHX,YVLFT,XVMOM,XSHFT,YSHFT
      READ(5,5921) ICF,DXC,JTF,DTH,IVIS,IT
      IF(IVIS.EQ.1)READ(5,100)XSTR,REC,       SH,RT
      IF(IVIS.EQ.1.AND.IT.EQ.0)READ(5,100)AH(1),BH(1),CH(1)
 5921 FORMAT(I5,E10.0,I5,E10.0,3I5)
      HI=FH(PI,WI,TI)
      PHI1=WI
      GI=FGAM(TI,PI,WI)
      RHI=RHEQ(HI,PI,WI,DUM)
      AI=SQRT(GI*PI/RHI)
      UI=EMI*AI
      XTHXI=XTHX
      YLFTI=YLFT
      XMOMI=XMOM
      XVTHXI=XVTHX
      YVLFTI=YVLFT
      XVMOMI=XVMOM
      DNUC=DNUC/57.3
      THI=THI/57.3
      DTH=DTH/57.3
      READ(5,100) AZ,BZ,CZ
      ZC1=GETZ(XC1)
      ZV1=GETZ(XV1)
      ZC2=GETZ(XC2)
      ZI=ZV1
```

```
5922 FORMAT(1H1/////)
     WRITE(6,1020)
1020 FORMAT(    14X*E Q U I L I B R I U M   F L O W   N O Z Z L E   D E
    1 S I G N*)
     WRITE(6,400) PI,THI,EMI,TI,GI,WI,PINF
 400 FORMAT(     ///30X,*INITIAL PROFILE*//3X*PRESSURE*7X*THETA*8X*MACH*
    16X*TEMPERATURE*5X*GAMMA*7X*PHI*8X*PINF*/7E13.5)
     WRITE(6,5930) XV1,YV1,XV2,XC1,YC1,XC2,DYV
5930 FORMAT(///6X*XV1*10X*YV1*10X*XV2*10X*XC1*10X*YC1*10X*XC2*10X*DYV*/
    17E13.5///)
1800 FORMAT(*  THRUST= *E13.5,7X*LIFT = *E13.5,7X*MOMENT= *E13.5)
     WRITE(6,1800)XTHX,YLFT,XMOM
1900 FORMAT(* VISCOUS THRUST= *E13.5,7X*VISCOUS LIFT= *E13.5,7X*
    1VISCOUS MOMENT= *E13.5)
     WRITE(6,1900)XVTHX,YVLFT,XVMOM
     WRITE(6,5923)XSHFT,YSHFT
5923 FORMAT(9X*MOMENT AXIS*/12X*X =*E13.5/12X*Y =*E13.5///)
     WRITE(6,1001) AZ,BZ,CZ
1001 FORMAT(9X*LATERAL EXPANSION EQUATION*/9X,22HZ(X) = AZ*X**2+BZ*X+CZ
    1/12X*AZ =*E13.5/12X*BZ =*E13.5/12X*CZ =*E13.5)
     RG=49800.
     RGAS=RG/WF
     CPI=G  F*RGAS/(G  F-1.)
     XC22=XC2
     THC1=THI-DNUC
     DO 5000 IXC=1,ICF
     XC2=XC22+FLOAT(IXC-1)*DXC
     YC2=YC1+TAN(THC1)*(XC2-XC1)
     YV2=YC2+DYV
     DNUV=ATAN((YV2-YV1)/(XV2-XV1))-THI
     CALL THM(RHI,UI,PI,HI,TI,EMI,GI,PINF,YV1,YC1,DYV,XV2,THRMAX,DNUV,
    1DNUC,XC2)
     WRITE(6,6364) THRMAX
6364 FORMAT(1H131X*IDEAL THRUST =*E12.4)
     YC2=YC1+TAN(THC1)*(XC2-XC1)
     YV2=YC2+DYV
     THC=ATAN((YC2-YC1)/(XC2-XC1))
     DO 6000 JT=1,JTF
     XTHX=XTHXI
     YLFT=YLFTI
     XMOM=XMOMI
     XVTHX=XVTHXI
     YVLFT=YVLFTI
     XVMOM=XVMOMI
     KSTP=50
     ISTP=50
     IEND=0
     IEXT=0
     IFLG=0
     IND=0
     THX=1.E+10
     THJT=FLOAT(JT-1)*DTH
     DNUV=ATAN((YV2-YV1)/(XV2-XV1))-THI+THJT
     WRITE(6,1894)DNUV
1894 FORMAT(* VEHICLE EXPANSION = *E13.5)
     XV=XV1
     AV=YV1
     BV=TAN(THI+DNUV)
     CV=0.
     YF1=AV+BV*(XF1-XV)
     IDUM=DNUV*57.3
     IF(IDUM.GT.11) IDUM=11
     IF(IDUM.EQ.0) IDUM=1
     DELNU=DNUV/FLOAT(IDUM)
     IDUM=IDUM+1
     IMAX=IDUM
```

```
      DO 10 I=1,IMAX
      X(1,I)=XV1
      Y(1,I)=YV1
      Z(1,I)=GETZ(XV1)
      TH(1,I)=THI+FLOAT(I-1)*DELNU
      M=I-1
      XNU(1,I)=FLOAT(I-1)*DELNU
      IF(I.NE.1)GO TO 8
      P(1,I)=PI$T(1,I)=TI$H(1,I)=HI$EM(1,I)=EMI$G(1,I)=GI$Q(1,I)=UI$
     1RH(1,I)=RHI
      GO TO 9
    8 CALL PM(DELNU,P(1,I),T(1,I),H(1,I),EM(1,I),G(1,I),Q(1,I),RH(1,I),
     1P(1,M),T(1,M),H(1,M),EM(1,M),G(1,M),Q(1,M),RH(1,M))
    9 XMU(1,I)=ASIN(1./EM(1,I))
   10 CONTINUE
      IDUM=DNUC*57.3
      IF(IDUM.GT.11) IDUM=11
      IF(IDUM.EQ.0) IDUM=1
      DELNU=DNUC/FLOAT(IDUM)
      IDUM=IDUM+1
      X(2,1)=XC1
      Y(2,1)=YC1
      Z(2,1)=GETZ(XC1)
      ICWL=0
      I=1
      THII=THI
      XNUI=0.
   20 CONTINUE
      TH(2,1)=THII-FLOAT(I-1)*DELNU
      XNU(2,1)=FLOAT(I-1)*DELNU+XNUI
      IF(I.NE.1)GO TO 86
      P(2,1) =PI$T(2,I)=TI$H(2,1)=HI$EM(2,1)=EMI$G(2,1)=GI$Q(2,1)=UI$
     1RH(2,1)=RHI
      GO TO 19
   86 CALL PM(DELNU,P(2,1),T(2,1),H(2,1),EM(2,1),G(2,1),Q(2,1),RH(2,1),
     1P(1,1),T(1,1),H(1,1),EM(1,1),G(1,1),Q(1,1),RH(1,1))
   19 XMU(2,1)=ASIN(1./EM(2,1))
   22 CONTINUE
      K=2
   36 CONTINUE
      IF(K.LT.KMAX) GO TO 41
      IF(IEND.EQ.1)GO TO 53
      CALL VWALL(IMAX,KMAX)
      MM=K-1
      L=K-1
      IF(ICWL.EQ.1)L=K
      IF(X(2,K).LT.XV2-EPS)GO TO 24
      CALL ENDD(L,MM,KMAX)
      X(2,K)=XV2
      IF(KSTP.GE.KMAX)KSTP=KMAX
      IND=1
      GO TO 17
   24 IF(I.GT.1) GO TO 30
      AV=Y(2,KMAX)
      BV=TAN(TH(2,KMAX))
      CV=(YV2-AV-BV*(XV2-X(2,KMAX)))/(XV2-X(2,KMAX))**2
      THV2=ATAN(BV+2.*CV*(XV2-X(2,KMAX)))
      XV=X(2,KMAX)
        IF(XF1.GT.XV)YF1=AV+BV*(XF1-XV)+CV*(XF1-XV)**2
      SLE=(YF1-YC2)/(XF1-XC2)
      IF(THV2.LT.0.) GO TO 462
      DO 16 KT=2,KMAX
      XK1=XK2=XK3=XK4=0.25
      M=KT-1
      J=KT-1
```

```
      N=0
      IF(KT.EQ.KMAX)J=KT-2
      IF(KT.EQ.2.OR.KT.EQ.KMAX)N=J
      IF(KT.EQ.2.OR.KT.EQ.KMAX)XK3=0.
      IF(KT.EQ.2.OR.KT.EQ.KMAX)XK1=XK2=XK4=.333333
      CALL LTHM(X(2,M),Y(2,M),Z(2,M),X(1,N),Y(1,N),Z(1,N),X(1,J),
     1Y(1,J),Z(1,J),X(2,KT),Y(2,KT),Z(2,KT),P(2,M),P(1,N),P(1,J),
     2P(2,KT),Q(2,M),Q(1,N),Q(1,J),Q(2,KT),T(2,M),T(1,N),T(1,J),
     3T(2,KT),TH(2,M),TH(1,N),TH(1,J),TH(2,KT),XK1,XK2,XK3,XK4,1.,
     4XTHX,YLFT,XMOM,CF(M),ST(M),3)
      IF(KT.EQ.KMAX)
     1CALL LTHM(X(1,J),Y(1,J),Z(1,J),X(1,J),Y(1,J),0.,X(2,KT),Y(2,KT),0.
     2,X(2,KT),Y(2,KT),Z(2,KT),P(1,J),P(1,J),P(2,KT),P(2,KT),Q(1,J),
     3Q(1,J),Q(2,KT),Q(2,KT),T(1,J),T(1,J),T(2,KT),T(2,KT),TH(1,J),
     4TH(1,J),TH(2,KT),TH(2,KT),.25,.25,.25,.25,1.,XTHX, YLFT, XMOM,
     5CFU,STU,1)
   16 CONTINUE
      GO TO 53
   41 CONTINUE
      IF(ICWL.EQ.1.AND.K.EQ.2.AND.IEXT.EQ.0)CALL CWALL(IMAX,KMAX,
     1KSTP,ISTP)
      IF(ICWL.EQ.1.AND.K.EQ.2.AND.IEXT.EQ.1)CALL CNT
      L=K
      IF(ICWL.EQ.1)L=K+1
      IF(I.EQ.1) L  =K-1
      LL=K+ICWL-1
      LM=L-1
      IF(L   .GT.ISTP.AND.IEND.EQ.1)GO TO 30
      MM=K-1
      CALL FIX(2,K-1,1,L   ,2,K)
      IF(I.EQ.1)GO TO 30
      IF(K.GT.1)SLA=(Y(2,K)-Y(2,MM))/(X(2,K)-X(2,MM))
      CALL GEM(X(2,MM),Y(2,MM),SLA,XC2,YC2,SLE,XC,YC)
      IF(XC.GE.X(2,K)  .OR.XC.LT.X(2,MM)-EPS)GO TO 30
      KSTP=K
      WRITE(6,88)KSTP,ISTP,KMAX,IMAX
   88 FORMAT(1X,4I5)
   30 CONTINUE
      LM=L-1
      IF(I.EQ.1)GO TO33
      IF(IEXT.EQ.1)GO TO 32
      IF(ICWL.EQ.0.OR.K.GT.2)GO TO 32
      CALL LTHM(X(1,1),Y(1,1),Z(1,1),X(2,1),Y(2,1),Z(2,1),X(2,1),
     1Y(2,1),0.,X(1,1),Y(1,1),0.,P(1,1),P(2,1),P(2,1),P(1,1),Q(1,1),
     2Q(2,1),Q(2,1),Q(1,1),T(1,1),T(2,1),T(2,1),T(1,1),TH(1,1),TH(2,1),
     3TH(2,1),TH(1,1),.25,.25,.25,.25,1.,XTHX, YLFT, XMOM,CFL,STL,2)
      CALL LTHM(X(1,1),Y(1,1),Z(1,1),X(1,2),Y(1,2),Z(1,2),X(2,1),Y(2,1),
     1Z(2,1),X(2,1),Y(2,1),Z(2,1),P(1,1),P(1,2),P(2,1),P(2,1),Q(1,1),
     2Q(1,2),Q(2,1),Q(2,1),T(1,1),T(1,2),T(2,1),T(2,1),TH(1,1),TH(1,2),
     3TH(2,1),TH(2,1),.33333,.33333,.33333,0.,1.,XTHX, YLFT, XMOM,
     4CF(1),ST(1),3)
   32 CONTINUE
      XK1=XK2=XK3=XK4=.25
      IF(IEND.EQ.0.AND.K.EQ.KMAX)GO TO 17
      AVG=4.
      SLB=(Y(2,K)-Y(1,L))/(X(2,K)-X(1,L))
      CALL GEM(X(1,L),Y(1,L),SLB,XC2,YC2,SLE,XC,YC)
      RAT=(XC- X(1,L))/(X(2,K)-X(1,L))
      IF(RAT.GT.0.99)GO TO 144
      IF(RAT.GT.0.)GO TO 143
      AVG=2.
      GO TO 144
  143 AVG=AVG-1.
  144 CONTINUE
      IF((X(2,MM)-X(1,LM)).EQ.0.)GOTO 148
```

```
      RAT =(XC-X(1,LM))/(X(2,MM)-X(1,LM))
      IF(RAT.GT.0.99)GO TO 148
      IF(RAT.GT.0.)GO TO 145
      AVG=AVG-2.
      GO TO 148
  145 AVG=AVG-1.
  148 CONTINUE
      AVG=AVG/4.
      CALL LTHM(X(2,MM),Y(2,MM),Z(2,MM),X(1,LM),Y(1,LM),Z(1,LM),X(1,L),
     1Y(1,L),Z(1,L),X(2,K),Y(2,K),Z(2,K),P(2,MM),P(1,LM),P(1,L),P(2,K),
     2Q(2,MM),Q(1,LM),Q(1,L),Q(2,K),T(2,MM),T(1,LM),T(1,L),T(2,K),
     3TH(2,MM),TH(1,LM),TH(1,L),TH(2,K),XK1,XK2,XK3,XK4,AVG,XTHX, YLFT,
     4XMOM,CF(LL),ST(LL),3)
      IF(IEND.EQ.1.OR.K.LT.KMAX)GO TO 33
   17 CONTINUE
      M=K-1
      L=M
      IF(ICWL.EQ.1)L=K
      AVG=3.
      SLA=(Y(2,K)-Y(2,M))/(X(2,K)-X(2,M))
      CALL GEM(X(2,M),Y(2,M),SLA,XC2,YC2,SLE,XC,YC)
      RAT=(XC-X(2,M))/(X(2,K)-X(2,M))
      IF(RAT.GT.0.99)GO TO 177
      AVG=AVG-1.
  177 SLB=(Y(2,M)-Y(1,L))/(X(2,M)-X(1,L))
      CALL GEM(X(1,L),Y(1,L),SLB,XC2,YC2,SLE,XC,YC)
      RAT=(XC-X(1,L))/(X(2,M)-X(1,L))
      IF(RAT.GT.0.99)GO TO 178
      IF(RAT.GT.0.)GO TO 173
      AVG=AVG-2.
  173 AVG=AVG-1.
  178 CONTINUE
      AVG=AVG/3.
      CALL LTHM(X(2,M),Y(2,M),Z(2,M),X(1,L),Y(1,L),Z(1,L),X(2,K),Y(2,K),
     1Z(2,K),X(2,K),Y(2,K),Z(2,K),P(2,M),P(1,L),P(2,K),P(2,K),Q(2,M),
     2Q(1,L),Q(2,K),Q(2,K),T(2,M),T(1,L),T(2,K),T(2,K),TH(2,M),TH(1,L),
     3TH(2,K),TH(2,K),.33333,.33333,.33333,0.,AVG,XTHX, YLFT, XMOM,
     4CF(LL),ST(LL),3)
   43 CALL LTHM(X(1,L),Y(1,L),Z(1,L),X(1,L),Y(1,L),0.,X(2,K),Y(2,K),
     10.,X(2,K),Y(2,K),Z(2,K),P(1,L),P(1,L),P(2,K),P(2,K),Q(1,L),Q(1,L),
     2Q(2,K),Q(2,K),T(1,L),T(1,L),T(2,K),T(2,K),TH(1,L),TH(1,L),TH(2,K),
     3TH(2,K),.25,.25,.25,.25,1.,XTHX, YLFT, XMOM,CFU,STU,1)
   33 IF(IEND.EQ.1)KMAX=ISTP
      K=K+1
      IF(K.LE.KMAX)GO TO 36
   53 KP=KMAX
      IF(IEND.EQ.1)KP=KMAX-1-ICWL
      IF(IND.EQ.1)IEND=1
      IND=0
      WRITE(6,6885)
 6885 FORMAT(1X*PT.*6X*X*11X*Y*8X*PRESSURE*5X*ANGLE*8X*MACH*4X*TEMPERATU
     1RE*1X*PM FUNCTION*3X*VELOCITY*)
      DO 50 L=1,KP
      WRITE(6,97) L,X(2,L),Y(2, L),P(2,L),TH(2,L),EM(2,L),T(2,L),XNU(2,
     1L),Q(2,L)
   50 CALL SWITCH(2,L,1,L)
      WRITE(6,2001)CFU,STU,CFL,STL
 2001 FORMAT(* VEH. FRIC. COEF= *E13.5,2X*VEH. STANTON NUM.= *E13.5,2X*
     1COWL FRIC. COEF.= *E13.5,2X*COWL STANTON NUM.= *E13.5)
      WRITE(6,450)
      NPR1=IMAX/5
      DO 166 K=1,NPR1
      K1=K$K2=K1+NPR1$K3=K2+NPR1$K4=K3+NPR1$K5=K4+NPR1
      KDONE=K5
```

```
     1CF(K4),ST(K4),CF(K5),ST(K5)
 166 CONTINUE
     IF(KDONE.EQ.IMAX)GO TO  55
     NPR2=5*NPR1+1
     DO 414 K=NPR2,IMAX
     WRITE(6,550)CF(K),ST(K)
 414 CONTINUE
  55 CONTINUE
 450 FORMAT(1X,5(6X,*CF *,9X,* ST   *,3X))
 500 FORMAT(1X,10E13.5)
 550 FORMAT(105X,2E13.5)
     WRITE(6,98)
     WRITE(6,1800)XTHX,YLFT,XMOM
     WRITE(6,1900)XVTHX,YVLFT,XVMOM
     IMAX=KMAX
     I=I+1
     IF(I.GT.IDUM)ICWL=1
     IF(ICWL.EQ.0)KMAX=KMAX+1
     IF(IEND.EQ.1)ISTP=KSTP+ICWL
     IF(IEND.EQ.1.AND.KP.EQ.1)GO TO 6000
     IF(IEND.EQ.1.AND.IEXT.EQ.1)GO TO 6000
     IF(IEXT.EQ.0.AND.X(1,1).GE.XC2-EPS)GO TO 5900
     IF(ICWL.EQ.1)GO TO 22
     GO TO 20
 462 CONTINUE
     WRITE(6,992)
 992 FORMAT(*THV2.LT.0*)
     GO TO 6000
5900 CONTINUE
     IF(P(1,1).LE.PF)GO TO 5396
     CALL COWL(DNUE)
     IDUM=6
     I=2
     XNUI=XNU(1,1)
     THII=TH(1,1)
     ICWL=0
     KMAX=KMAX+1
     DELNU=DNUE/FLOAT(IDUM)
     IDUM=IDUM+1
     IEXT=1
     GO TO 20
5396 CONTINUE
6000 CONTINUE
5000 CONTINUE
     END
```

```
      SUBROUTINE CWALL(IMAX,KMAX,KSTP,ISTP)
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50),H(2,50),RH(2,50),
     2G(2,50)
      COMMON/C/DNUV,DNUC,XC1,YC1,XV1,YV1,DNUL
      COMMON/CWL/XC2,YC2
      D=0.
      IADD=0
      LOOP=0
      XTHM1=TH(1,1)-XMU(1,1)
      Q1=XNU(1,1)-TH(1,1)
      CALL INT(0.,X(1,2),Y(1,2),Z(1,2),TH(1,2),XNU(1,2),P(1,2),T(1,2),
     1H(1,2),EM(1,2),G(1,2),Q(1,2),RH(1,2),XMU(1,2),
     2D,D,D,D,D,D,D,D,D,D,D,D,D,
     2XA,YA,ZA,THA,XNUA,PA,TA,HA,EMA,GA,UA,RHA,XMUA,-1.)
      Q2=XNU(1,2)-TH(1,2)
   44 XTHM2=THA-XMUA
      IF(LOOP.EQ.0)XTHM3=XTHM2
      SLA=(TAN(XTHM2)+TAN(XTHM3))/2.
      SLB=(YC2-YC1)/(XC2-XC1)
      CALL GEM(XA     ,YA     ,SLA,XC2,YC2,SLB,XC,YC)
      IF(XC.LE.XC2)GO TO 43
      IADD=1
      DX=X(1,2)-X(1,1)
      SLU=(Y(1,2)-Y(1,1))/DX
      IT=1
      XA=(X(1,2)+X(1,1))/2.
   24 RAT=(XA-X(1,1))/DX
      SLB=XTHM1+RAT*(XTHM2-XTHM1)
      SLB=TAN(SLB)
      IF(LOOP.EQ.1)SLB=(SLB+TAN(XTHM3))/2.
      CALL GEM(X(1,1),Y(1,1),SLU,XC2,YC2,SLB,XAT,YA)
      ER=ABS((XA-XAT)/DX)
      IF(ER.LT.1.E-04)GO TO 63
      IT=IT+1
      IF(IT.GT.10)GO TO 68
      XA=XAT
      GO TO 24
   68 WRITE(6,38)
   38 FORMAT(* TOO MANY ITER IN CWALL *)
      WRITE(6,39)LOOP,SLU,SLB,XA,XAT
   39 FORMAT(1X,I5,5E13.5)
      STOP
   63 CONTINUE
      CALL INT(RAT,X(1,1),Y(1,1),Z(1,1),TH(1,1),XNU(1,1),P(1,1),T(1,1),
     1H(1,1),EM(1,1),G(1,1),Q(1,1),RH(1,1),XMU(1,1),X(1,2),Y(1,2),
     2Z(1,2),TH(1,2),XNU(1,2),P(1,2),T(1,2),H(1,2),EM(1,2),G(1,2),
     3Q(1,2),RH(1,2),XMU(1,2),XA,YA,ZA,THA,XNUA,PA,TA,HA,EMA,GA,UA,
     4RHA,XMUA,-1.)
   43 RA=THA+XNUA
      IF(ABS(XC2-XC).LE..0001)XC=XC2
      X(2,1)=XC
      Y(2,1)=YC
      Z(2,1)=GETZ(XC)
      TH(2,1)=TH(1,1)
      XNU(2,1)=RA-TH(2,1)
      DNU=XNU(2,1)-XNUA
      CALL PM(DNU ,P(2,1),T(2,1),H(2,1),EM(2,1),G(2,1),Q(2,1),RH(2,1),
     1PA,TA,HA,EMA,GA,UA,RHA)
      RQ3D=RH(2,1)*W(2,1)/Z(2,1)
      DNU3=DNU
      ITT=1
```

```
      ERT=.001
   10 CONTINUE
      CALL PM(DNU3,P(2,1),T(2,1),H(2,1),EM(2,1),G(2,1),Q(2,1),RH(2,1),
     1PA,TA,HA,EMA,GA,UA,RHA)
      RQT=RH(2,1)*Q(2,1)
      ERQ=(RQT-RQ3D)/RQ3D
      IF(ITT.GE.10)ERT=.005
      IF(ABS(ERQ).LT.ERT)GO TO 20
      CALL ERROR(1,ITT,DNU3,ERQ,1.1,DNUZ1,ERQZ1)
      GO TO 10
   20 CONTINUE
      XMU(2,1)=ASIN(1./EM(2,1))
      XTHM3=TH(2,1)-XMU(2,1)
      IF(LOOP.EQ.1)GO TO 6
      LOOP=1
      GO TO 44
    6 IF(IADD.EQ.0)RETURN
      IMAX=IMAX+1
      KMAX=KMAX+1
      KSTP=KSTP+1
      ISTP=ISTP+1
      DO 46 JJ=3,IMAX
      LJ=IMAX-JJ+3
      L1=LJ-1
   46 CALL SWITCH(1,L1,1,LJ)
      WRITE(6,181)IADD,XA,X(1,1),X(1,2)
  181 FORMAT(1X,I5,3E13.5)
      CALL INT(0.,XA,YA,ZA,THA,XNUA,PA,TA,HA,EMA,GA,UA,RHA,XMUA,
     1D,D,D,D,D,D,D,D,D,D,D,D,D,X(1,2),Y(1,2),Z(1,2),TH(1,2),XNU(1,2),
     2P(1,2),T(1,2),H(1,2),EM(1,2),G(1,2),Q(1,2),RH(1,2),XMU(1,2),-1.)
      RETURN
      END
```

```
      SUBROUTINE ENDD(L,KK,K6)
      COMMON/V/AV,BV,CV,XV,YV2,YV2
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50),H(2,50),RH(2,50),
     2G(2,50)
      ITT=1
      B=0.
      A=1.
      XM1=TH(1,L )+XMU(1,L )
      XM2=TH(2,KK)+XMU(2,KK)
      XM3=0.
      Q1=TH(1,L )+XNU(1,L )
      Q2=TH(2,KK)+XNU(2,KK)
      XA=(X(1,L )+X(2,KK))/2.
      DX=X(2,KK)-X(1,L )
      SLM=(Y(2,KK)-Y(1,L ))/DX
   12 RAT=(XA-X(1,L ))/DX
      SLP=XM1+RAT*(XM2-XM1)
      SLP=A*SLP+B*XM3
      CALL GEM(X(1,L ),Y(1,L ),SLM,XV2,YV2,SLP,XAT,YA)
      ER=ABS((XA-XAT) /DX)
      IF(ER.LT.1.E-03)GO TO 14
      ITT=ITT+1
      IF(ITT.LE.10)GO TO 8
      WRITE(6,33)
   33 FORMAT(* TOO MANY ITER IN END *)
      WRITE(6,34)L,KK,K6,XA,XAT,X(2,KK),X(1,L),SLP,XM3
   34 FORMAT(1X,3I5,6E13.5)
      STOP
    8 XA=XAT
      GO TO 12
   14 QA=Q1+RAT*(Q2-Q1)
      CALL INT(RAT,X(1,L),Y(1,L),Z(1,L),TH(1,L),XNU(1,L),P(1,L),
     1T(1,L),H(1,L),EM(1,L),G(1,L),Q(1,L),RH(1,L),XMU(1,L),X(2,KK),
     2Y(2,KK),Z(2,KK),TH(2,KK),XNU(2,KK),P(2,KK),T(2,KK),H(2,KK),
     3EM(2,KK),G(2,KK),Q(2,KK),RH(2,KK),XMU(2,KK),XA,YA,ZA,THA,XNUA,
     4PA,TA,HA,EMA,GA,QA,RHA,XMUA,1.)
      RA=XNUA-THA
      X(2,K6)=XV2
      Y(2,K6)=YV2
      Z(2,K6)=GETZ(XV2)
      TH(2,K6)=ATAN (BV+2.*CV*(XV2-XV))
      XNU(2,K6)=RA+TH(2,K6)
      DNU=XNU(2,K6)-XNUA
      CALL PM(DNU ,P(2,K6),T(2,K6),H(2,K6),EM(2,K6),G(2,K6),Q(2,K6),
     1RH(2,K6),PA,TA,HA,EMA,GA,QA,RHA)
      RQ3D=RH(2,K6)*Q(2,K6)/Z(2,K6)
      DNU3=DNU
      IT=1
      ERT=.001
   10 CONTINUE
      CALL PM(DNU3,P(2,K6),T(2,K6),H(2,K6),EM(2,K6),G(2,K6),Q(2,K6),
     1RH(2,K6),PA,TA,HA,EMA,GA,QA,RHA)
      RQT=RH(2,K6)*Q(2,K6)
      ERQ=(RQT-RQ3D)/RQ3D
      IF(IT.GE.10)ERT=.005
       IF(ABS(ERQ).LT.ERT)GO TO 16
      CALL ERROR(2,IT,DNU3,ERQ,1.1,DNUZ1,ERQZ1)
      GO TO 10
   16 XMU(2,K6)=ASIN(1./EM(2,K6))
      IEND=1
      IF(B.GT.0.)RETURN
```

```
      B=.5
      A=.5
      XM3=TH(2,K6)+XMU(2,K6)
      GO TO 12
      END
```

```
      SUBROUTINE INT(RAT,X1,Y1,Z1,TH1,XNU1,P1,T1,H1,EM1,G1,U1,RH1,XMU1,
     1X2,Y2,Z2,TH2,XNU2,P2,T2,H2,EM2,G2,U2,RH2,XMU2,X3,Y3,Z3,TH3,
     2XNU3,P3,T3,H3,EM3,G3,U3,RH3,XMU3,OPT)
      HT1=H1+U1*U1/2.
      HT2=H2+U2*U2/2.
      Q1=XNU1+OPT*TH1
      Q2=XNU2+OPT*TH2
      X3=X1+RAT*(X2-X1)
      Y3=Y1+RAT*(Y2-Y1)
      Q3=Q1+RAT*(Q2-Q1)
      P3=P1+RAT*(P2-P1)
      T3=T1+RAT*(T2-T1)
      XNU3=XNU1+RAT*(XNU2-XNU1)
      TH3=(Q3-XNU3)/OPT
      HT3=HT1+RAT*(HT2-HT1)
      U3=U1+RAT*(U2-U1)
      G3=G1+RAT*(G2-G1)
      H3=H1+RAT*(H2-H1)
      RH3=RH1*(P3/P1)**(1./G3)
      EM3=U3/SQRT(G3*P3/RH3)
      XMU3=ASIN(1./EM3)
      Z3=GETZ(X3)
      RETURN
      END
```

```
      SUBROUTINE THM(RHI,UI,PI,HI,TI,EMI,GI,PINF,YV1,YC1,DYV,XV2,THRMAX,
     1DNUV,DNUC,XC2)
      COMMON/D3/AZ,BZ,CZ
      A1=YV1-YC1
      F1=RHI*UI*A1
      Z2=AZ*XV2*XV2+BZ*XV2+CZ
      Z5=AZ*XC2*XC2+BZ*XC2+CZ
      A2=(Z2+Z5)/2.*DYV
      IT=1
      DNU=(DNUV+DNUC)*SQRT((Z2+Z5)/2.)
   10 CALL PM(DNU,P2,T2,H2,EM2,G2,U2,RH2,PI,TI,HI,EMI,GI,UI,RHI)
      F2=RH2*U2*A2
      ERT=(F2-F1)/F1
      IF(ABS(ERT).LT.1.E-04) GO TO 20
      CALL ERROR(99,IT,DNU,ERT,.9,DNU1,ERT1)
      GO TO 10
   20 TH1=(PI-PINF+RHI*UI*UI)*A1
      TH2=(P2-PINF+RH2*U2*U2)*A2
      THRMAX=TH2-TH1
      RETURN
      END
```

```
      SUBROUTINE EM3D(EM,EMX,X,G,Z,ZI)
      GN=(G+1.)/(G-1.)/2.
      Y=(1.+(G-1.)/2.*EM*EM)**GN
      Y=Y/EM/((G+1.)/2.)**GN
      A=Y*Z/ZI
      EMX=EM*SQRT(Z)
      ITM=1
   10 AT=(1.+(G-1.)/2.*EMX*EMX)**GN
      AT=AT/EMX/((G+1.)/2.)**GN
      ERM=(AT-A)/A
      IF(ABS(ERM).LT.1.E-03) GO TO 20
      CALL ERROR(100,ITM,EMX,ERM,1.1,EMX1,ERM1)
      GO TO 10
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SWITCH(I2,K,I1,L)
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50),H(2,50),RH(2,50),
     2G(2,50)
      X  (I1,L)=X  (I2,K)
      Y  (I1,L)=Y  (I2,K)
      Z  (I1,L)=Z  (I2,K)
      TH (I1,L)=TH (I2,K)
      XNU(I1,L)=XNU(I2,K)
      P  (I1,L)=P  (I2,K)
      T  (I1,L)=T  (I2,K)
      H(I1,L)=H(I2,K)
      G(I1,L)=G(I2,K)
      RH(I1,L)=RH(I2,K)
      EM (I1,L)=EM (I2,K)
      XMU(I1,L)=XMU(I2,K)
      Q(I1,L)=Q(I2,K)
      RETURN
      END
```

```
FUNCTION GETZ(X)
COMMON/D3/ AZ,BZ,CZ
GETZ=AZ*X**2+BZ*X+CZ
RETURN
END
```

```
      SUBROUTINE VWALL (IMAX,KMAX)
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50),H(2,50),RH(2,50),
     2G(2,50)
      COMMON/V/AV,BV,CV,XV,XV2,YV2
      COMMON/C/DNUV,DNUC,XC1,YC1,XV1,YV1,DNUL
      IBEG=0
      ITW=1
      SL2=TH(1,IMAX)
      SL1=TAN(TH(2,KMAX-1)+XMU(2,KMAX-1))
      SL13=SL1
      CALL GEM(X(2,KMAX-1),Y(2,KMAX-1),SL1,X(1,IMAX),Y(1,IMAX),SL2,
     1XG,YG)
   12 YW=AV+BV*(XG-XV)+CV*(XG-XV)**2
      ERW=(YW-YG)/(YV1-YC1)
      IF(ABS(ERW).LT.1.E-02) GO TO  10
      CALL ERROR(3,ITW,XG,ERW,.9,XG1,ERW1)
      YG=Y(2,KMAX-1)+SL13*(XG-X(2,KMAX-1))
   10 TH(2,KMAX)=ATAN(BV+2.*CV*(XG-XV))
      XNU(2,KMAX)=TH(2,KMAX)-TH(2,KMAX-1)+XNU(2,KMAX-1)
      X(2,KMAX)=XG
      Y(2,KMAX)=YG
      Z(2,KMAX)=GETZ(XG)
      K=KMAX
      M=KMAX-1
       DNU=XNU(2,K)-XNU(2,M)
      CALL PM(DNU ,P(2,K),T(2,K),H(2,K),EM(2,K),G(2,K),Q(2,K),RH(2,K),
     1P(2,M),T(2,M),H(2,M),EM(2,M),G(2,M),Q(2,M),RH(2,M))
      RQ3D=RH(2,K)*Q(2,K)/Z(2,K)
      DNU3=DNU
      IT=1
      ERT=.001
   15 CONTINUE
      CALL PM(DNU3,P(2,K),T(2,K),H(2,K),EM(2,K),G(2,K),Q(2,K),RH(2,K),
     1P(2,M),T(2,M),H(2,M),EM(2,M),G(2,M),Q(2,M),RH(2,M))
      RQT=RH(2,K)*Q(2,K)
      ERQ=(RQT-RQ3D)/RQ3D
      IF(IT.GE.10)ERT=.005
      IF(ABS(ERQ).LT.ERT)GO TO 16
      CALL ERROR(4,IT,DNU3,ERQ,1.1,DNUZ1,ERQZ1)
      GO TO 15
   16 CONTINUE
      XMU(2,K)=ASIN(1./EM(2,K))
      IF(IBEG.EQ.1) RETURN
      IBEG=1
      SL13=.5*(SL1+TAN(TH(2,KMAX)+XMU(2,KMAX)))
      GO TO 12
      END
```

```
      SUBROUTINE GEM(XA,YA,SLA,XB,YB,SLB,XC,YC)
      XC=(YB-YA+SLA*XA-SLB*XB)/(SLA-SLB)
      YC=YA+SLA*(XC-XA)
      RETURN
      END
```

```
      SUBROUTINE ERROR (I,IT,X,ER,F,X1,ER1)
      IT=IT+1
      IF(IT.LT.15) GO TO 12
      WRITE(6,13)
   13 FORMAT(*ERROR TEST NUMBER *)
      WRITE (6,20) I
   20 FORMAT(I5)
      STOP
   12 IF(IT.GT.2) GO TO 14
      ER1=ER
      X1=X
      X=X*F
      IF(X.EQ.X1) X=X+.02
      RETURN
   14 XD=X1-ER1*(X-X1)/(ER-ER1)
      ER1=ER
      X1=X
      X=XD
      RETURN
      END
```

```
      SUBROUTINE FIX(I1,K1,I2,K2,I3,K3)
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50),H(2,50),RH(2,50),
     2G(2,50)
      DUM3=0.
      DUM4=0.
      A=1.
      B=0.
      DUM1=TAN(TH(I1,K1)+XMU(I1,K1))
      DUM2=TAN(TH(I2,K2)-XMU(I2,K2))
      XNU(I3,K3)=.5*(XNU(I1,K1)+XNU(I2,K2)+TH(I2,K2)-TH(I1,K1))
      TH(I3,K3)=.5*(XNU(I2,K2)-XNU(I1,K1)+TH(I2,K2)+TH(I1,K1))
   10 IF(B.GT.0.) DUM3=TAN(TH(I3,K3)+XMU(I3,K3))
      IF(B.GT.0.) DUM4=TAN(TH(I3,K3)-XMU(I3,K3))
      SL1=A*DUM1+B*DUM3
      SL2=A*DUM2+B*DUM4
      CALL GEM(X(I1,K1),Y(I1,K1),SL1,X(I2,K2),Y(I2,K2),SL2,X(I3,K3),
     1Y(I3,K3))
      Z(I3,K3)=GETZ(X(I3,K3))
      DNU=XNU(I3,K3)-XNU(I1,K1)
      CALL PM(DNU ,P(I3,K3),T(I3,K3),H(I3,K3),EM(I3,K3),G(I3,K3),
     1Q(I3,K3),RH(I3,K3),P(I1,K1),T(I1,K1),H(I1,K1),EM(I1,K1),
     2G(I1,K1),Q(I1,K1),RH(I1,K1))
      RQ3D=RH(I3,K3)*Q(I3,K3)/Z(I3,K3)
      ERT=.001
      DNU3=DNU
      IT=1
   12 CONTINUE
      CALL PM(DNU3,P(I3,K3),T(I3,K3),H(I3,K3),EM(I3,K3),G(I3,K3),
     1Q(I3,K3),RH(I3,K3),P(I1,K1),T(I1,K1),H(I1,K1),EM(I1,K1),
     2G(I1,K1),Q(I1,K1),RH(I1,K1))
      RQT=RH(I3,K3)*Q(I3,K3)
      ERQ=(RQT-RQ3D)/RQ3D
      IF(IT.GE.10)ERT=.005
      IF(ABS(ERQ).LT.ERT)GO TO 20
      CALL ERROR(5,IT,DNU3,ERQ,1.1,DNUZ1,ERQZ1)
      GO TO 12
   20 XMU(I3,K3)=ASIN(1./EM(I3,K3))
      IF(B.GT.0.) RETURN
      A=.5
      B=.5
      GO TO 10
      END
```

```
      SUBROUTINE PM(DNU,P2,T2,H2,EM2,G2,U2,RH2,PI,TI,HI,EMI,GI,UI,RHI)
      COMMON/D/ PHI1
      DTH=1./57.3
      IFAN=ABS(DNU)/DTH+1
      DUM=DNU
      IF(IFAN.GT.1)DUM=DNU/FLOAT(IFAN-1)
      P1=PI
      T1=TI
      EM1=EMI
      H1=HI
      G1=GI
      RH1=RHI
      A1=SQRT(G1*P1/RH1)
      U1=UI
      U1=U1*U1
      HT=H1+U1/2.
      P1=ALOG(P1)
      XNU=0.
      XNU1=0.
      IF(IFAN.NE.1)IFAN=IFAN-1
      DO 10 I=1,IFAN
      XMU1=ASIN(1./EM1)
      B1=G1*EM1/COS(XMU1)
      P2=-B1*DUM+P1
      RH2=(P2-P1)/G1
      RH2=RH1*EXP(RH2)
      P2P=EXP(P2)
      P1P=EXP(P1)
      U2=U1-2.*G1/(G1-1.)*(P2P/RH2-P1P/RH1)
      H2=HT-U2/2.
      T2=FT(P2P,PHI1,H2)
      G2=FGAM(T2,P2P,PHI1)
      A2=G2*P2P/RH2
      EM2=SQRT(U2/A2)
      XNU=XNU1+DUM
      XNU1=XNU
      P1=P2
      T1=T2
      G1=G2
      EM1=EM2
      U1=U2
      RH1=RH2
   10 CONTINUE
      P2=EXP(P2)
      U2=SQRT(U2)
      RETURN
      END
      END
```

```
      SUBROUTINE PMI(IX,KX)
      COMMON/IN/PI,TI,AI,THI,EMI,GI,ZI,HI,RHI,UI
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50),H(2,50),RH(2,50),
     2G(2,50)
      COMMON/P/PINF,PTOT,TTOT
      COMMON/CP/CPI,       RGAS
      DNU=XNU(IX,KX)
      G=GI
      EM1=EMI
      GG=SQRT((G+1.)/(G-1.))
      XM1=SQRT(EM1**2-1.)
      XNU1=GG*ATAN(XM1/GG)-ATAN(XM1)
      EM2=DNU/(1.5-XNU1)*(6.-EM1)+EM1
      IT3=1
   10 XM2=SQRT(EM2**2-1.)
      DNUT=GG*(ATAN(XM2/GG)-ATAN(XM1/GG))+ATAN(XM1)-ATAN(XM2)
      ERNU=DNU-DNUT
      IF(ABS(ERNU).LT.1.E-04) GO TO 20
      CALL ERROR(6,IT3,EM2,ERNU,1.11,EM21,ERNU1)
      GO TO 10
   20 CONTINUE
      CALL EM3D(EM2,EMX,X(IX,KX),G,Z (IX,KX),ZI)
      P(IX,KX)=PTOT/(1.+(G-1.)/2.*EMX**2)**(G/(G-1.))
      T(IX,KX)=TTOT/(1.+(G-1.)/2.*EMX**2)
      EM(IX,KX)=EMX
      XMU(IX,KX)=ASIN(1./EMX)
      AX=SQRT(G*RGAS*T(IX,KX))
      Q(IX,KX)=EMX*AX
      RETURN
      END
```

```
      SUBROUTINE GNURE(RH,Q,P,T,R,          X,X1,CF,ST,L)
      COMMON/CP/CPI,     RGAS
      COMMON/O/PHI1
      COMMON/HOT/AH(3),BH(3),CH(3),XSTR,  REC,        RT,SH,IT,IVIS
      HDEL=R-Q*Q/2.
      HAW=1.+REC*Q*Q/2./HDEL
      IF(IT .EQ.0)TW=AH(L)*(X-X1)**2+BH(L)*(X-X1)+CH(L)
      IF(IT .EQ.1)GO TO 46
      HW=FH(P,PHI1,TW)
      HW=HW/HDEL
      GO TO 48
   46 HW=HAW
   48 A=HAW-1.
      B=HW-1.
      C=SQRT((A+B)**2+4.*A)
      FC=A/(ASIN((A-B)/C)+ASIN((A+B)/C))**2
      FRX=HAW**(.772)/(FC*(HW)**(1.474))
      CALL VIS(T,XMMU)
      REX=RH*Q*(X+XSTR)*RT /XMMU
      REXI=FRX*REX
      CFI=.088*(ALOG10(REXI)-2.3686)/(ALOG10(REXI)-1.5)**3
      CF=CFI/FC
      ST=CF*SH/2.
      RETURN
      END
      SUBROUTINE VIS(T,XMUU)
      XMUU=2.27*T**1.5*1.E-08/(T+198.6)
      RETURN
      END
```

```
      SUBROUTINE SNARF(X1,Y1,Z1,X2,Y2,Z2,X3,Y3,Z3,X4,Y4,Z4,AVX,AVY,AVZ,
     1XNX,XNY,XNZ,AS,X0,Y0,Z0,LH)
      DIMENSION XPA(4),YPA(4),ZPA(4),XI(4),ETA(4)
      XPA(1)=X1
      YPA(1)=Y1
      ZPA(1)=Z1
      ZPA(2)=Z2
      YPA(2)=Y2
      XPA(2)=X2
      XPA(3)=X3
      YPA(3)=Y3
      ZPA(3)=Z3
      ZPA(4)=Z4
      YPA(4)=Y4
      XPA(4)=X4
      T1X=X3-X1
      T1Y=Y3-Y1
      T1Z=Z3-Z1
      T2X=X4-X2
      T2Y=Y4-Y2
      T2Z=Z4-Z2
      XNX=T2Y*T1Z-T1Y*T2Z
      XNY=T1X*T2Z-T2X*T1Z
      XNZ=T2X*T1Y-T1X*T2Y
      VN=SQRT(XNX**2+XNY**2+XNZ**2)
      IF(VN.LE.1.E-13)GO TO 6
      XNX=XNX/VN
      XNY=XNY/VN
      XNZ=XNZ/VN
      D=XNX*(AVX-X1)+XNY*(AVY-Y1)+XNZ*(AVZ-Z1)
      PD=ABS(D)
      T=SQRT(T1X*T1X+T1Y*T1Y+T1Z*T1Z)
      T1X=T1X/T
      T1Y=T1Y/T
      T1Z=T1Z/T
      T2X=XNY*T1Z-XNZ*T1Y
      T2Y=XNZ*T1X-XNX*T1Z
      T2Z=XNX*T1Y-XNY*T1X
      DO 1000 J=1,4
      XPA(J)=XPA(J)+XNX*D
      YPA(J)=YPA(J)+XNY*D
      ZPA(J)=ZPA(J)+XNZ*D
      D=-D
      XDIF=XPA(J)-AVX
      YDIF=YPA(J)-AVY
      ZDIF=ZPA(J)-AVZ
      XI(J)=T1X*XDIF+T1Y*YDIF+T1Z*ZDIF
 1000 ETA(J)=T2X*XDIF+T2Y*YDIF+T2Z*ZDIF
      XI0=(XI(4)*(ETA(1)-ETA(2))+XI(2)*(ETA(4)-ETA(1)))/(ETA(2)-ETA(4))
     1/3.
      ETA0=-ETA(1)/3.
      DO 1020 J=1,4
      XI(J)=XI(J)-XI0
 1020 ETA(J)=ETA(J)-ETA0
      X0=AVX+T1X*XI0+T2X*ETA0
      Y0=AVY+T1Y*XI0+T2Y*ETA0
      Z0=AVZ+T1Z*XI0+T2Z*ETA0
      AS=(ETA(2)-ETA(4))*(XI(3)-XI(1))/2.
      AS=ABS(AS)
      RETURN
    6 CONTINUE
      X0=AVX $ Y0=AVY $ Z0=AVZ
```

```
      RS=0.
      RETURN
      END

      SUBROUTINE CTHM(X1,Y1,Z1,X2,Y2,Z2,X3,Y3,Z3,X4,Y4,Z4,P1,P2,P3,P4,
     1Q1,Q2,Q3,Q4,T1,T2,T3,T4,TH1,TH2,TH3,TH4,XK1,XK2,XK3,XK4,AVG,
     2XXTHX,XYLFT,XXMOM,CFF,ST,LH)
      COMMON/O/PHI1
      COMMON/P/PINF,PTOT,TTOT
      COMMON/CP/CPI,      RGAS
      COMMON/SHF/XSHFT,YSHFT
      COMMON/HOT/AH(3),BH(3),CH(3),XSTR,  REC,        RT,SH,IT,IVIS
      COMMON/VISF/XVTHX,YVLFT,XVMOM
      P=XK1*P1+XK2*P2+XK3*P3+XK4*P4
      Q=XK1*Q1+XK2*Q2+XK3*Q3+XK4*Q4
      T=XK1*T1+XK2*T2+XK3*T3+XK4*T4
      TH=XK1*TH1+XK2*TH2+XK3*TH3+XK4*TH4
      H=FH(P,PHI1,T)
      RH=RHEQ(H,P,PHI1,DUM)
      R=H+Q*Q/2.
      R=CPI*T+Q*Q/2.
      AVX=XK1*X1+XK2*X2+XK3*X3+XK4*X4
      AVY=XK1*Y1+XK2*Y2+XK3*Y3+XK4*Y4
      AVZ=XK1*Z1+XK2*Z2+XK3*Z3+XK4*Z4
      CALL SNARF(X1,Y1,Z1,X2,Y2,Z2,X3,Y3,Z3,X4,Y4,Z4,AVX,AVY,AVZ,XNX,
     1XNY,XNZ,ASS,XO,YO,ZO,LH)
      CFF=0.
      XBP=0.
      IF(IVIS.EQ.1)CALL GNURE(RH,Q,P,T,R,       XO,XBP,CFF,ST,1 )
      RHQ=RH*Q*Q/2.
      PAV=P-PINF
      DXTHX=-PAV*XNX*ASS
      DYLFT= PAV*XNY*ASS
      XNZZ=1.
      IF(LH.EQ.3)XNZZ=XNZ
      DXTHXV=-CFF              *COS(TH)*ASS*RHQ
      DYLFTV=CFF        *SIN(TH)*ASS*RHQ
      DXTHXV=DXTHXV*AVG
      DYLFTV=DYLFTV*AVG
      XMS=XO-XSHFT
      YMS=YO-YSHFT
      DMOMV=YMS*DXTHXV+XMS*DYLFTV
      XVTHX=XVTHX+DXTHXV
      YVLFT=YVLFT+DYLFTV
      XVMOM=XVMOM+DMOMV
      DXTHX=DXTHX*AVG+DXTHXV
      DYLFT=DYLFT*AVG+DYLFTV
      DMOM=YMS*DXTHX+XMS*DYLFT
      XXTHX=XXTHX+DXTHX
      XYLFT=XYLFT+DYLFT
      XXMOM=XXMOM+DMOM
      RETURN
      END
```

```
      SUBROUTINE CNT
      COMMON/IN/PI,TI,XI,THI,EMI,GI,ZI,QI,RHI,UI
      COMMON/CNTC/TTC,PTC,XC,GC,PC,THC,XNUC,ZC,EMC
      COMMON/P/PINF,PTOT,TTOT
      COMMON/CP/CPI,       RGAS
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50),H(2,50),RH(2,50),
     2G(2,50)
      A=1. $ B=0.
                                  GIS=GI $ZIS=ZI$EMIS=EMI
      ITT=1
      RB=XNU(1,2)+TH(1,2)
      TH(2,1)=TH(1,1)
   20 SLA=A*TAN(TH(2,1))+B*TAN(TH(1,1))
      SLB=TH(1,2)-XMU(1,2)
      SLB=A*TAN(SLB)
      IF(B.GT.0.)SLB=SLB+B*TAN(TH(2,1)-XMU(2,1))
      CALL GEM(X(1,2),Y(1,2),SLB,X(1,1),Y(1,1),SLA,X(2,1),Y(2,1))
      Z(2,1)=GETZ(X(2,1))
      XNU(2,1)=RB-TH(2,1)
      DNU=XNU(2,1)-XNU(1,1)
      CALL PM(DNU ,P(2,1),T(2,1),H(2,1),EM(2,1),G(2,1),Q(2,1),RH(2,1),
     1P(1,1),T(1,1),H(1,1),EM(1,1),G(1,1),Q(1,1),RH(1,1))
      RQ3D=RH(2,1)*Q(2,1)/Z(2,1)
      DNU3=DNU
      ERT=.001
      IT=1
   10 CONTINUE
      CALL PM(DNU3,P(2,1),T(2,1),H(2,1),EM(2,1),G(2,1),Q(2,1),RH(2,1),
     1P(1,1),T(1,1),H(1,1),EM(1,1),G(1,1),Q(1,1),RH(1,1))
      RQT=RH(2,1)*Q(2,1)
      ERQ=(RQT-RQ3D)/RQ3D
      IF(IT.GE.10)ERT=.005
      IF(ABS(ERQ).LT.ERT)GO TO 14
      CALL ERROR(7,IT,DNU3,ERQ,1.1,DNUZ1,ERQZ1)
      GO TO 10
   14 XMU(2,1)=ASIN(1./EM(2,1))
      TTOT=TTC $ PTOT=PTC $ GI=GC $ZI=ZC $EMI=EMC
      RC=XNUC-THC
      TH(2,2)=TH(2,1)
      XNU(2,2)=RC+TH(2,2)
      X(2,2)=X(2,1)
      Y(2,2)=Y(2,1)
      Z(2,2)=GETZ(X(2,2))
      CALL PMI(2,2)
      ER3=(P(2,1)-P(2,2))/PC
      IF(ABS(ER3).LT.1.E-04)GO TO 16
      CALL ERROR(8 ,ITT,TH(2,1),ER3,1.01,TH23,ER23)
                                  GI=GIS $ZI=ZIS $EMI=EMIS
      GO TO 20
   16 CONTINUE
                                  GI=GIS $ZI=ZIS $EMI=EMIS
      IF(B.GT.0.)RETURN
      ITT=1
      A=.5 $ B=.5
      GO TO 20
      END
```

```
      SUBROUTINE COWL(DNUE)
      COMMON/X/X(2,50),Y(2,50),Z(2,50),TH(2,50),XNU(2,50),
     1P(2,50),T(2,50),EM(2,50),XMU(2,50),Q(2,50),H(2,50),RH(2,50),
     2G(2,50)
      COMMON/CWL/XC2,YC2
      COMMON/P/PINF,PTOT,TTOT
      COMMON/F/PF,TF,WF,THF,EMF,GF
      COMMON/CP/CPI,      RGAS
      COMMON/CNTC/TTC,PTC,WC,GC,PC,THC,XNUC,ZC,EMC
      PCC=(PF+P(1,1))/2.
      GM1=GF-1.
      GP1=GF+1.
      EMF2=EMF*EMF
      DUM=1.+GM1*EMF2/2.
      PTF=PF*DUM**(GF/GM1)
      TTF=TF*DUM
      GIS=GI
      XMUF=ASIN(1./EMF)
      IT=1
      BET=(THF-XMUF+TH(1,1))*1.1-THF
   20 DUM=(EMF*SIN(BET))**2
      PC=(2.*GF*DUM-GM1)/GP1
      TC=PC*(GM1*DUM+2.)/DUM/GP1
      EMC=(EMF2*(GP1*PC+GM1)-2.*(PC*PC-1.))/(GM1*PC+GP1)/PC
      EMC=SQRT(EMC)
      PC=PC*PF
      THC=TAN(BET)*(GP1*EMF2/(DUM-1.)/2.-1.)
      THC=ATAN(1./THC)+THF
      PTC=(2.*TC/(GM1*EMF2+2.))**(GF/GM1)
      PTC=PC/PTC
      TTC=TTF
      TC=TC*TF
      RA=XNU(1,1)+TH(1,1)
      X(2,1)=XC2 $Y(2,1)=YC2 $TH(2,1)=THC
      Z(2,1)=GETZ(XC2)
      XNU(2,1)=RA-TH(2,1)
      DNU=XNU(2,1)-XNU(1,1)
      CALL PM(DNU ,P(2,1),T(2,1),H(2,1),EM(2,1),G(2,1),Q(2,1),RH(2,1),
     1P(1,1),T(1,1),H(1,1),EM(1,1),G(1,1),Q(1,1),RH(1,1))
      ER4=(PC-P(2,1))/PCC
      IF(ABS(ER4).LT.1.E-03)GO TO 16
      CALL ERROR(9,IT,BET,ER4,1.05,BET1,ER41)
      GO TO 20
   16 DNUE=XNU(2,1) -XNU(1,1)
      GI=GIS
      WC=WF
      GC=GF
      ZC=Z(2,1)
      XNUC=0.
      RETURN
      END
```

```
      FUNCTION FH(P1,F,T1)
      P=P1*1.01325E+05/2116.
      T=T1/1.8
      F2=F*F
      IF(F.LT.0.) GU TO 400
      IF(T.GT.2000.) GO TO 190
      IF(F.GT.1.) GO TO 191
  120 A=1.E-07*(-.1042*F2  +.8242*F+.987)
      B=.001*(.01167*F2 +.1503*F+.938)
      C=-.0284*F2 +.6731*F+.4293
      GO TO 290
  191 A=1.E-07*(1.787*F2 -5.48*F+5.4)
      B=.001*(-.1867*F2 +1.11*F+.176)
      C=-.0933*F2 +3.975*F-2.808
      GO TO 290
  190 IF(F.GT.1.) GO TO 192
      A=.000001*(1.792*F2 +.3983*F+.31)
      B=.001*(-9.05*F2 -.07917*F+.245)
      C=10.86*F2 -.1183*F+.97
      GO TO 290
  192 A=.000001*(4.81*F2 -13.9*F+11.59)
      B=.001*(-23.08*F2 +66.82*F-52.61)
      C=27.05*F2 -73.73*F+58.39
  290 H1=A*T*T+6*T+C
      IF(T.LE.2000.) GO TO 370
      A10=ALOG(P)/2.3-5.
      Z9=.125*A10*A10                 -.275*A10
      H1=H1*(1.+(1.+F)*(T/2000.-1.)*Z9)
  370 H1=H1*1.E+06
      GO TO 340
  400 T2=T*T
      T3=T2*T
      T4=T3*T
      T5=T4*T
      H1=A1*T+A2*T2/2.+A3*T3/3.+A4*T4/4.+A5*T5+A6
      H1=H1*8314./XMM1
  340 CONTINUE
      FH=H1*10.7639
      RETURN
      END
```

```
      FUNCTION FT(P1,F,H5)
      DATA I63/0/
      IFLAG=0
      P=P1*1.01325E+05/2116.
      H=H5     /10.7639/1.E+06
      F2=F*F
      A10=ALOG(P)/2.3-5.
      Z9=.125*A10*A10            -.275*A10
      IT=1
      IF(I63.EQ.1) GO TO 1000
      I63=1
      T=1500.
      T0=1500.
      IF(F.GE.0.) GO TO 120
      T=600.
      T0=T
 000  CONTINUE
      IF(F.LT.0.) GO TO 400
      GO TO 120
  50  E0=(H-H1)/H
      IF(ABS(E0).LT.1.E-04) GO TO 340
 500  T =T0*1.1
 502  IT=2
      IF(F.LT.0.) GO TO 400
      GO TO 120
 100  E1=(H-H1)/H
      IF(ABS(E1).LT.1.E-04) GO TO 340
      IT=IT+1
      IF(IT.LT.21) GO TO 10
      IF(ABS(T-2000.).LT.10.) GO TO 830
      WRITE(6,831) P1,H5,T
 31   FORMAT(* ERROR IN FT*/* P1 = *E13.5,5X,*H1 = *E13.5,5X,*T = *E13.5
     1)
      STOP
 30   IF(IFLAG.EQ.1) GO TO 504
      IFLAG=1
      T0=2000.
      T=2000.
      IF(F.LT.0.) GO TO 400
      GO TO 120
 04   WRITE(6,11)   E1
 11   FORMAT(* TEMPERATURE IN FT SET TO 2000      -      ERROR = *E13.5)
      GO TO 340
 10   T9=T0-E0*(T -T0)/(E1-E0)
 05   E0=E1
      T0=T
      T=T9
      IF(F.LT.0.) GO TO 400
 20   A=1.E-07*(-.1042*F2  +.8242*F+.987)
      B=.001*(.01167*F2 +.1503*F+.938)
      C=-.0284*F2 +.6731*F+.4293
      IF(F.LE.1.) GO TO 190
      A=1.E-07*(1.787*F2 -5.48*F+5.4)
      B=.001*(-.1867*F2 +1.11*F+.176)
      C=-.0933*F2 +3.975*F-2.808
 0    IF(T.LE.2000.) GO TO 290
      A=.000001*(1.792*F2 +.3983*F+.31)
      B=.001*(-9.05*F2 -.07917*F+.245)
      C=10.86*F2 -.1183*F+.97
      IF(F.LE.1.) GO TO 290
      A=.000001*(4.81*F2 -13.9*F+11.59)
      B=.001*(-23.08*F2 +66.82*F-52.61)
```

```
      IF(T.LE.2000.) GO TO 370
      H1=H1*(1.+(1.+F)*(T/2000.-1.)*Z9)
  370 CONTINUE
      GO TO 350
  400 T2=T*T
      T3=T2*T
      T4=T3*T
      T5=T4*T
      IF(F.LT.-1.5) GO TO 450
      XMM1=16.043
      A1=4.2497678
      A2=-6.9126562E-03
      A3=3.1602134E-05
      A4=-2.9715432E-08
      A5=9.5103580E-12
      A6=-1.0186632E+04
      GO TO 460
  450 CONTINUE
      A1=1.1202436
      A2=1.3905716E-02
      A3=2.6568374E-06
      A4=-1.1560272E-08
      A5=5.2386929E-12
      A6=5.3328896E+03
      XMM1=28.054
  460 H1=A1*T+A2*T2/2.+A3*T3/3.+A4*T4/4.+A5*T5+A6
      H1=H1*8314./XMM1/1.E+06
  350 IF(IT.EQ.1) GO TO 50
      GO TO 100
  [illegible]0 T0=T
      FT=T*1.8
      RETURN
      END
```

```
      FUNCTION RHEQ(H,P1,F,T)
      T1=FT(P1,F,H)
      T=T1/1.8
      P=P1*1.01325E+05/2116.
      IF(F.LT.0.) GO TO 2260
      FNM=1.53*F*F-5.895*F+28.965
      FNN=1.6*F*F-10.6*F+33.6
      IF(T.GT.2000.) GO TO 2030
      XM=FNM
      IF(F.LT.1.) GO TO 2160
      XM=FNN
      GO TO 2160
 2030 FF=F*F
      A=-2.3*FF+4.01*F+1.736
      B=8.61*FF-15.42*F-6.66
      C=-16.88*FF+33.21*F+14.58
      XN=-.4375*FF+.0625*F+2.08
      D=A*(ALOG(P)/2.3)**1.5+B*(ALOG(P)/2.3)+C
      XM=FNM-D*((T-2000.)/1000.)**XN
      IF(F.LT.1.) GO TO 2160
      A=-.822*FF+2.363*F+1.905
      B=2.76*FF-7.56*F-8.68
      C=-3.6*FF+7.36*F+27.15
      XN=-.47*FF+1.825*F+.35
      D=A*(ALOG(P)/2.3)**1.5+B*(ALOG(P)/2.3)+C
      XM=FNN-D*((T-2000.)/1000.)**XN
      GO TO 2160
 2260 KF=F-.5
      IF(KF.EQ.-1)XM=16.043
      IF(KF.EQ.-2)XM=28.054
 2160 RHEQ=P*XM/T/8314.3*6.2428E-02/32.174
      T=T*1.8
      RETURN
      END
```

```
      FUNCTION FGAM(T1,P1,F)
      T=T1/1.8
      T2=T*T
      P=P1*1.01325E+05/2116.
      XM=0.
      IF(F.LT.0.) GO TO 550
      IF(T.LE.1000.) GO TO 440
      XM=-2.15E-08*T2 +.000091*T-.0695
  440 XN=4.E-09*T2 -.00002*T-.019
      IF(F.LE.1.) GO TO 470
      XN=.0339*SQRT(T)-.000391*T-.681
  470 G=-1.833E-07*T2 +.000075*T+1.367
      IF(T.LT.500.) GO TO 520
      G=2.E-08*T2 -.000138*T+1.423
      IF(T.LT.2000.) GO TO 520
      G=7.267E-08*T2 -.000457*T+1.85
  520 G=G+XM*(ALOG(P)/2.3-5.)+XN*(F-1.)
      GO TO 530
  550 T3=T2*T
      T4=T3*T
      CP=A1+A2*T+A3*T2+A4*T3+A5*T4
      G=CP*(CP-1.)
  530 CONTINUE
      FGAM=G
      RETURN
      END
```

```
#
926.3     3970.2    1.        0.        2.776     21.443
52.96     488.8     28.965    0.        8.636     1.4
0.        1.        18.54     1.11      0.        3.12      7.866     6.
6.

    5     .5        5    1.
0.        0.        1.
```